Evaluation of the potential of non-woody invasive plant biomass for electricity generation

by
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Declaration

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Abstract

Invasive alien plants (IAPs) threaten the existence of plant and animal biodiversity as they cause destruction to the natural habitats they invade. In South Africa the Natural Resource Management (NRM) programme clears these plants. In efforts to add value to the clearing operation, the NRM Programme's objective is to utilise the cleared IAP biomass for economic purposes, thereby contributing to the sustainable management and control of invasive species.

The objectives of this study were to assess the potential and the economic viability to supply non-woody IAP biomass for electricity generation.

The study was conducted on biomass samples from 13 common non-woody IAPs in South Africa namely: *Arundo donax* (Giant reed), *Lantana camara* (Lantana), *Pontederia cordata* (Pickerel weed), *Ricinus communis* (Castor-oil plant), *Opuntia ficus-indica* (Sweet prickly pear), *Solanum mauritianum* (Bugweed), *Atriplex nummunlaria* (Saltbush), *Cestrum laevigatum* (Inkberry), *Senna didymobotrya* (PB Cassia), *Chromoleana odorata* (Chromoleana), *Eichhornia crassipes* (Water hyacinth), *Cerus jamacaru* (Queen of the night) and the *Agave sisilana* (Sisal plant). Properties, such as density, moisture content, calorific value, ash content and volatile content, elemental composition as well as processability and estimated drying time were determined in order to assess the suitability of the biomass for different thermo-chemical conversion techniques (combustion, gasification and pyrolysis). This study only assessed the potential of non-woody IAPs for electricity generation, with the main focus on thermochemical conversion. Although some of the species might be suitable for bio-chemical conversion, a detailed overview of biochemical pathways is beyond the scope of this study.

The second part of the study examined the economic and financial perspective of the biomass supply to generate electricity, in which the harvesting, chipping and transport costs of the biomass were considered.

The results of this study showed that non-woody invasive biomass has the potential to be used as feedstock for electricity generation through combustion. None of the species were found to be suitable for gasification or pyrolysis due to their high silica, chlorine and ash content. Sweet prickly pear, Water hyacinth, Queen of the night, Sisal, Pickerel weed and the Castor-oil plant had a too high moisture content and would be best suited for energy production through biochemical conversion pathways. The total average cost to harvest and transport non-woody

IAP chips to an energy plant was R33/GJ, which is approx. 50% more expensive than other biomass feedstocks (Forestry residues and woody IAPs).

Overall when taking physical, chemical and financial aspects into consideration Giant reed, Saltbush, and Chromoleana were the best species to be utilised as feedstock. However, without a "fuel cost subsidy" from the NRM programme, the harvesting of non-woody alien invasive species for energy production is unlikely to be financially viable.

Opsomming

Indringerplante bedreig die voortbestaan van plant en dier biodiversiteit omdat hulle natuurlike habitate indring en vernietig. In Suid Afrika word hierdie plante verwyder deur die Natuurlike Hulpbron Bestuur (NHB) program. In pogings om waarde toe te voeg tot skoonmaakoperasies het die NHB program ‘n doelwit om die verwyderde indringer biomassa te gebruik vir ekonomiese doeleindes. Hierdie doelwit dra by tot die volhoubare bestuur en kontrole oor indringerplante.

Die doelwitte van hierdie studie was om die potensiaal en ekonomiese volhoubaarheid van die voorsiening van nie-houdagtig indringerplante vir elektrisiteitsopwekking te ondersoek. Die studie is uitgevoer op biomassa mosters van 13 van die mees algemene nie-houdagtige indringerplante in Suid Afrika, genaamd: *Arundo donax* (Spaansriet), *Lantana camara* (Lantana), *Pontederia cordata* (Jongsnoekkruid), *Ricinus communis* (Kasterolieplant), *Opuntia ficus-indica* (Soet turksvy), *Solanum mauritianum* (Luisboom), *Atriplex nummunlaria* (Soutbos), *Cestrum laevigatum* (Inkbessie), *Senna didymobotrya* (Grondboontjiebotterkassia), *Chromoleana odorata* (Parafienbos), *Eichhornia crassipes* (Waterhiasint), *Cerus jamacaru* (Nagblom) and the *Agave sisilana* (Sisalplant). Eienskappe soos digtheid, voginhoud, kalorifiesewaarde, as-inhoud, vlugtigheidsinhoud, elementsamestelling sowel as verwerkbaarheid en droogtyd is bepaal om sodoende die geskiktheid van die biomassa vir verskillende termo-chemiese omsettings metodes te bepaal (verbranding, gassifikasie en pirolise).

Die studie het slegs die potensiaal van nie-houtagtige indringerplante vir elektrisiteitsopwekking ondersoek met die hoof fokus op termo-chemiese omsetting. Alhoewel sommige van die spesies geskik mag wees vir bio-chemiese omsetting is ‘n gedetaileerde oorsig van die bio-chemiese prosesse buite die bestek van die studie.

Die tweede deel van die studie ondersoek die ekonomiese en finansiele perspektief van biomasa voorsiening om elektrisitiet op te wek. Dit sluit in die ontginning, versnippering en vervoerkostes van die biomassa.

Die resultate van die studie wys dat nie-houdagtige indringer biomassa die potensiaal het om as roumateriaal gebruik te word vir elektrisiteits generasie deur verbranding. Geen van die

spesies was geskik vir gassifasie of pirolisie weens hoë silica, chloor en as inhoud. Soet turksvy, Waterhiasint, Nagblom, Sisal, Jongsnoekkruid en die Kasterolieplant het 'n te hoë voginhoud en sal mees geskik wees vir bio-chemise opsettings metodes. Die totale gemiddelde koste van ontginning en vervoer van nie-houdagtige indringerplante tot by die energie aanleg was R 33/GJ, wat nagenoeg 50% duurder is as ander biomass roumateriaal (Bosbou residu en houtagtige indringerplante). Ontginning en vervoerkostes vergelyk ongunstig met die van biomassa roumateriaal tipes soos bosbou afval en houdagtige indringerplante.

Wanneer die fisiese, chemiese en finansiele aspekte oorweeg word is Spaansriet, Soutbos en Parafienbos die beste spesies vir bio-energie roumateriaal. Sonder 'n brandstof subsidie vanaf die NHB program is die ontginning van nie-houdagtige indringerspesies vir energie produksie nie finansieel haalbaar nie.

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To my parents, David Tanduxolo and Nophelo Melane and brothers, Mfundo, Mawande, and Bandile Melane-thank you for your constant prayers, moral support and words of encouragement.

Dedications

This thesis is dedicated to my late grandparents Weston and Lillian Nomahinisa Melane. You dedicated your life to ensuring your future generations have a better life. We continue to benefit from your sacrifices. Thank you.

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List of Abbreviations and Acronyms

AC	Ash content
C	Carbon
Cl	Chlorine
HHV	Higher heating value
IAPs	Invasive alien plants
LHV	Lower heating value
MC	Moisture content (% weight basis)
N	Nitrogen
NEM:BA	National Environmental Management: Biodiversity Act
NIAPS	National Invasive Alien Plants Survey
NRM	Natural Resource Management
PD	Person days'
RE	Renewable energy
S	Sulphur
Si	Silicon
VM	Volatile matter
WfW	Working for Water
WIMS	Water Information Management System

List of units

GJ	Gigajoule
ha	Hectare
kg	Kilogram
kWh	Kilowatt hour
MW	Megawatt
t	tonne

1 Introduction

1.1 Background to the study

Conventional fossil fuel-based energy sources have come under scrutiny for being environmentally unfriendly and unsustainable. This led to a rising interest in renewable energy sources, such as wind and bioenergy, especially in Europe where there are dedicated plantations for energy wood (Panoutsou *et al*. 2011).

The use of biomass of invasive alien plants (IAPs) as potential feedstock for bioenergy production has been studied by various researchers in many countries (Young *et al*. 2011; Mugido *et al*. 2013; Liao *et al*. 2013; Amaduccii and Perego 2015); and it is predicted that future biomass resources for bioenergy would be from forest and agricultural residues, including invasive plant species.

In South Africa, where arable land is in short supply (Kotze and Rose 2015; Government of South Africa, 2016), energy plantations might be seen as a threat to food security and biodiversity, prompting a stronger focus on the use of IAP and agricultural/ forestry residue for bioenergy use. Whilst IAPs are freely available, the main concern to economic sustainability is the harvesting and transportation of invasive plants (Young *et al*. 2011).

The potential use of woody invasive alien plants for energy purposes in South Africa has been well documented (Munalula and Meincken 2009; Smit 2010; Mugido *et al*. 2013). Munalula and Meincken (2009) determined the best alternative of fuel wood from a list of invasive species. Mugido *et al*. (2013) conducted a study to determine the feasibility of harvesting woody IAPs for energy purposes in the Eastern Cape.

However, there is limited knowledge of the potential of using non-woody IAPs for bioenergy in South Africa. Thus, it is important that studies are undertaken to understand the costs, risks, sustainability, impact on farmers, potential for jobs and value in clearing non-woody IAPs for bioenergy purposes (DEA 2015).

1.2 Problem statement

Invasive alien plants have significant negative effects on the environment in South Africa, because they invade natural ecosystems and degrade the biodiversity in these systems (Le Maitre *et al*. 2011). The impacts of woody IAPs are far-reaching creating both economic and ecological losses, with the most substantial impact being on water availability (Marais *et al*. 2001). With South Africa being a water scarce country these water losses pose a threat to the economy of the country (De Lange *et al*. 2012). An independent survey of major invasive plants in South Africa by Kotze (2010) shows, however, that invasive trees have spread at a rate greater than clearing and eradication efforts take place.

The invasion of IAPs poses management challenges, which require a combination of approaches to eradicate the problem. The primary goal of the NRM Working for Water (WfW) programme in South Africa is to control the spread of existing IAPs. The creation of employment through the programme is an added advantage. Initially the financial benefits of the programme were limited to utilizing the wood as firewood, furniture and crafts, but additional options for bioenergy have been explored to further reduce the financial burden of clearing (Working for Water 2014). The use of non-woody IAPs for bioenergy generation could serve as an alternative option.

The purpose of this study is to assess and compare the feasibility to supply non-woody IAPs from South Africa as feedstock for electricity generation.

1.3 Research methodology

1.3.1 Research objectives

The main objective was to investigate the potential of selected non-woody IAPs in South Africa for electricity generation by considering physical, chemical and financial aspects.

1.3.2 Research questions

The key questions addressed in this study are:

1. Can non-woody invasive alien plants be used to generate electricity?
2. What are the most suitable processing options for the different species in order to be suitable for thermo-chemical energy producing technologies?
3. Are the biomass supply costs for these non-woody invasive species economically feasible?

1.3.3 Methodology

The study started with the assessment of biomass from 13 non-woody species from different climatic zones identified by NRM studies as problematic and the characterisation of the biomass by determining moisture content (MC), loose density, heating value (HV), ash content (AC), volatile content (VC) and the elemental composition carbon (C), nitrogen (N), sulphur (S), silica (Si), chlorine (Cl). From this characterisation it was possible to rank the biomass according to its suitability for thermochemical energy conversion processes, based on physical and chemical properties. Some species were discarded at this stage, due to e.g. too high ash, S, Si or Cl content or too low density.

Furthermore, the suitability of the different species with regards to comminution (chipping, milling, grinding etc.) was determined. Some species were eliminated in this step, where processing was too complicated (for example too soft plant parts that could not be chipped or milled).

1.3.4 Economic feasibility of the IAP biomass to electricity chain

The second objective of the study was to perform an economic feasibility analysis to determine the costs associated with the biomass supply of non-woody IAPs to an electricity plant. Several studies have performed detailed economic analysis of woody biomass-fired electricity generation (Mamphweli 2009; IRENA 2012; ICFR 2013; Mugido *et al*. 2013; STEAG 2013; Pierce 2015), but few have analysed the feasibility of using non-wood biomass.

This study focused on identifying the most cost effective biomass to electricity value chain option, by comparing the cost of value chain activities to deliver a unit (GJ) of energy. The processing costs include the cost of harvesting, extracting, chipping and transporting IAPs based on their energy density. Based on this, the focus of this study was to identify the non-woody species with the highest potential to be utilised for conversion to electricity and to investigate the economic feasibility for each species, as well as the cost effectiveness throughout the value chain. Non-woody invasive species might have potential as feedstock for bioenergy production. While there might be enough material available for bioenergy production, the economic viability of the biomass production value chain is highly influenced by market conditions, especially in South Africa where the market for bioenergy is not well developed (Petrie and Macqueen 2013; Turpie 2014). Other factors that could affect the success of biomass to bioenergy value chain include the choice of feedstock and feedstock procurement, pre-processing, transport, chosen conversion technology, timescale, scale, as well as costs of operations throughout the biomass-to- bioenergy value chain (ECN 2014). These factors are discussed in more detail in chapter 2.

The Eskom fuel supply study estimated that up to 80% of IAP and bush encroachment biomass is available from the biomass resources available in South Africa. The biomass produced from clearing operations of IAPs could be a great source of biomass to generate energy for the next 20-year period (Stafford 2014). According to Petrie (2005) biomass to energy offers a cost-effective way to manage, and hopefully eradicate, alien and invasive species while lessening the national electricity crisis and providing upliftment to rural communities. This includes the creation of products relevant to the government's needs, as well as creating jobs for local communities.

2 Background and literature review

In this chapter the current challenges that South Africa faces with the spread of IAPs are discussed. Various global bioenergy applications that utilize IAPs as feedstock in efforts to eradicate the problem of invasiveness and the related challenges are reviewed. Furthermore, the economic feasibility of the biomass-to- bioenergy conversion is discussed.

2.1 Invasive alien plant species in South Africa

As a result of globalisation physical barriers between countries have become less effective and the spread of exotic species has become much easier. The widespread distribution of invasive plants poses a threat to biodiversity and land productivity. IAPs suppress the growth of indigenous species and in extreme cases replace them in the ecosystem, even to the extent of extinction (Bromilow 2001). This threatens the integrity of ecosystems and provision of ecosystem services, as the fauna associated with the indigenous species also becomes threatened. As a result the resilience of ecosystems is weakened, making them more susceptible to events, such as fire, floods and other catastrophes (Bromilow 2001). Young *et al.* (2011) added that invasive plants could out-compete native species by using more water, light and oxygen, because they are often vigorous growers. IAPs also have a high adaptability to grow in a range of habitats and often outgrow native species by producing large amounts of seeds, as they are introduced to a new continent without natural enemies (van Wilgen *et al*. 2004).

2.1.1 History of introductions to South Africa

South Africa is a very diverse country with many biomes including thicket, grassland, forest, fynbos and savanna, which host a variety of plant and animal life. Invasive species can be found throughout these landscapes. The problem of invasive plants in South Africa dates back to 1913 when alien cacti (*Opuntia* species) invaded semi-arid rangelands (Macdonald 2004). Invasion of fynbos plant communities by *Pinus*, *Eucalyptus* and *Hakea* species were reported early as 1930 (Macdonald 2004; DEA 2014). Most of the prominent invader species were introduced from outside of Africa for commercial applications - for timber (Pines, Eucalypts), bark extraction for tannin (*Acacia mearnsii*), for environmental applications, either as wind barriers (e.g. *Acacia dealbata*), as cover crops (e.g. *Acacia saligna*, *A. cyclops*), as ornamentals (e.g.

Melia azedarach and *Lantana camara*) or by accident as contaminants of seeds or fodder for horses (van Wilgen *et al*. 2001; Bromilow 2001; Henderson 2007; DEA 2014). Many of these invasive species became established in South African ecosystems (van Wilgen *et al*. 2001; DEA 2014). There are approximately 9000 alien plant species that have been introduced into South Africa (DEA 2014), of which approximately 1000 have become naturalised (Saunders 2012), and 381 are invasive alien plants that require management under the environmental biodiversity act (NEM:BA). According to Le Maitre *et al*. (1997) these invasive species (mainly trees and woody shrubs) cover an estimated 10.1 million ha (8.28%) of South Africa and Lesotho.

All of the most productive pine species are invasive (Richardson 1998), but although they are classified as conflict species in South Africa, they commercially important forestry trees. The impact of Pine invasions on biodiversity is high especially in the fynbos biome (Chamier *et al*. 2012; DEA 2014; van Wilgen 2015). Although alien trees and shrubs have contributed to the economy (Saunders 2012), the impact of alien plant invasions on natural resources in South Africa poses a threat because they use a large amount of water, spread quickly, outcompete native species, intensify fires and increase soil erosion (Chamier *et al*. 2012). These negative impacts can lower biodiversity, agricultural potential, and affect the provision of ecosystem services (Saunders 2012).

2.1.2 National legislation dealing with invasive plant species

In South Africa the current legislative and policy framework governing the management of invasive species is the National Environmental Management: Biodiversity (NEM:BA) Act No. 10 of 2004. Under the Department of Environmental Affairs (DEA), the Act provides the framework for monitoring, control and eradication of invasive species in South Africa. NEM: BA regulations classify invasive plants into four groups: Category 1a, 1b, 2 and 3. Plants listed in Category 1a are declared weeds and are therefore, prohibited from being grown or planted. Their seeds, cuttings or propagated material may not be transported. These species are targeted for national eradication (DEA 2014). Category 1b invasive species require on- going control as part of a management plan (DEA 2014) and their spread needs to be controlled. Examples of category 1b plants include *Arundo donax, Cestrum laevigatum, Cereus jamacaru, Chromoleana odorata, Eichhhornia crassipes, Lantana camara* etc. (NEM:BA 2004). Category 2 plant invaders are those that have commercial value and can be grown under permit conditions. These species include *Pinus patula, Agave sisilana, Atriplex nummularia, Acacia* *mearnsii, Eucalyptus grandis, etc*. (NEM:BA 2004*)*. Plant invaders in Category 3 include popular ornamental plants such as *Jacaranda mimosifolia, Melia azedarach,* etc. Since they do not cause excessive harm they are permitted to be grown in some provinces provided that they are kept under control (within 30m from the 1:50 year flood line of watercourses) (DEA 2014).

2.1.3 Impacts of invasive plants

In South Africa, invasive plants have an impact mainly on water resources and biodiversity. Meijninger and Jarmain (2014) studied the impact of IAPs and found that invaded areas had higher evapotranspiration rates when compared to most natural vegetation. The most distinctive characteristic of invasive species, however, is the difficulty to control their spread. De la Fontaine (2013) studied the possible impact of IAPs on livelihoods and well-being of rural land-users in the Agulhas region and found that IAPs had a detrimental impact on the ecosystem services, which support people's livelihoods, because they consumed vast amounts of water and increased the fire hazard on the land.

Impacts on water resources

Water use by IAPs has been the subject of research in South Africa since 1970s (Görgens and van Wilgen 2004). Various studies have found that some IAPs have significant effects on water resources (stream flow) in South Africa (Le Maitre *et al*. 2000; Marais *et al*. 2001; Görgens and van Wilgen 2004; van Wilgen *et al*. 2007). The surface water use of IAPs was estimated at over 3 000 million m^3 annually (~ 7% MAR, Le Maitre *et al*. 2000). According to van Wilgen *et al*. (2007) the impacts of IAPs on surface water runoff are highest in the fynbos (shrubland) and grassland biomes. However, Saunders (2012) cautioned that this information be put into context as trees in general use more water than shrubs, therefore, water use by IAPs in grasslands will increase. IAP invasions from Pines, Eucalypts and wattle which have higher evaporation rates than indigenous species result in stream flow reduction (depending on annual rainfall), thereby increasing the presence of pollutants and nutrients in the river as well as increasing its salinity (Görgens and van Wilgen 2004; Chamier *et al*. 2012).

Impacts on biodiversity and the environment

The estimated losses due to biodiversity and provisioning of ecosystem services are estimated at R570 million per year (DEA 2004). The most detailed effects of tree invasions on biodiversity in South Africa have been illustrated in the Cape Floristic Region, where *Pinus* species escaped from commercial plantations into the fynbos areas, changing the dynamics of the area and reducing its capacity to produce ecosystem services (van Wilgen *et al*. 2001; van Wilgen *et al*. 2007). Plant invasions by tall trees lead to increased plant material especially in grassland and scrublands, resulting in increased fire intensity that damages the soil (Chamier *et al*. 2012; Saunders 2012). Furthermore, there could be changes in nitrogen fixation as a result of increased biomass material (van Wilgen *et al*. 2001; Chamier *et al*. 2012). The presence of IAPs, such as Wattle (*Acacia* spp.), Pom-pom weed (*Campulonliniumm scrocephalum*) and Famine weed *(Parthenium hysterophorus*) poses a threat to grasslands in South Africa (Saunders 2012; DEA 2014). Famine weed produces harmful chemicals that are toxic to both humans and animals (DEA 2014). Other examples of devastating IAPs include Water hyacinth (*Eichhornia crassipes*), an aquatic weed that degrades aquatic ecosystems and affects the health of rivers and estuaries by blocking sunlight and oxygen (van Wilgen *et al.* 2001). Sweet Prickly pear (*Opuntia ficus-indica*) has invaded and degraded the farming potential of large tracts of land in the Eastern Cape and Karoo (DEA 2014). Although it is difficult to quantify the environmental impacts of IAPs in monetary terms, the economic impacts can be severe (van Wilgen *et al*. 2001).

2.1.4 Invasive species management in South Africa

In 1995 the Working for Water (WfW) programme was established to manage established invasive alien plants (mainly trees and shrubs) in catchment areas across all major terrestrial biomes in South Africa, with the purpose of reducing the impact on water resources (Richardson and van Wilgen 2004; Chamier *et al*. 2012; DEA 2014). The programme's annual budget has increased from R400 million in 2002 (Görgens and van Wilgen 2004) to over R1.22 billion for 2014/2015 (DEA 2014). However, according to van Wilgen *et al*. (2012) the control operations had little effect on the extent of invasions and species, such as *Chromoleana odorata* remained the same and in some cases the invasion even increased. However, the programme has been effective with its combination of mechanical and biological control of some species and reducing the extent of their impact (van Wilgen *et al*. 2012).

The benefits of clearing IAPs include fire fuel reduction, conservation of biodiversity, preservation of ecosystems, improved ecosystem services, increase in water quality, erosion control, value added industries and job creation. As some of these IAPs contain utilizable wood, an opportunity exists to use the biomass produced from the clearing of IAPs to generate bioenergy and other value added products (Turpie et al. 2014). The use of IAPs for bioenergy production will contribute to reducing the invasion and restoring the invaded ecosystems. Therefore, the clearance of IAPs for use in bioenergy production is desirable, but it is critical to establish the viability of such a venture (Mugido *et al.* 2013).

2.1.5 Distribution of invasive alien plants in South Africa

Invasive alien plants have invaded approximately 10 million hectares (8.28%) of the South African landscape (Meijninger and Jarmain 2014). Various studies have provided estimates of available biomass of IAPs in South Africa, Lesotho and Swaziland (Versfeld *et al*. 1998; Henderson 2007; Kotze *et al.* 2010; Le Maitre *et al*. 2011), with each study focusing on particular species and using different methods. To date, the National Invasive Alien Plant Survey by Kotze *et al*. (2010) has the most comprehensive set of records. Le Maitre *et al*. (2011) who used the National Invasive Alien Plant Survey by Kotze *et al*. (2010) as reference, estimated that there are approximately 165 million tonnes of woody IAPs in South Africa (see Figure 1) spread over 44 million ha (DEA 2015a).

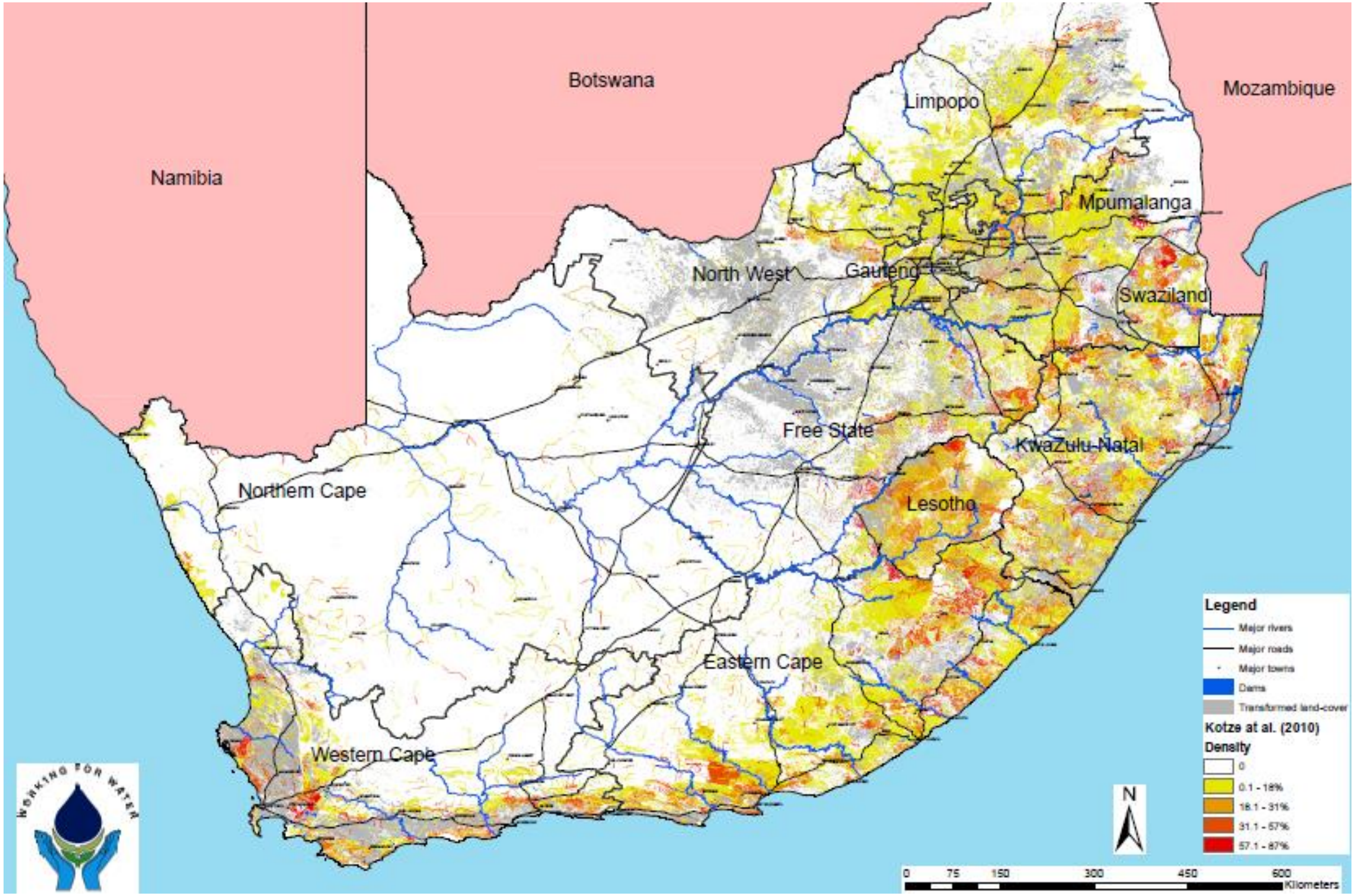

Figure 1: The invasive alien plant infestation survey map for South Africa, Swaziland and Lesotho (Kotze *et al*. 2010).

The survey indicates that woody invasive biomass is the most abundant form of IAPs in South Africa according to habitat, invasion density and extent of invasion. The distribution of invaders varies between biomes and regions.

Van Wilgen *et al*. (2012) listed the *Acacia*, *Pinus* and *Hakea* species as the most abundant woody IAPs in the fynbos region. Grassland and savannah biomes are invaded by a variety of woody scramblers, such as Triffid weed (*Chromoleana odorata*), Brambles (*Rubus* species) and Giant reed (*Arundo donax*) along rivers. In arid areas, Mesquite (*Prosopis* species) can be found in dry riverbeds and Lantana (*Lantana camara*) in grasslands (Richardson and van Wilgen 2004).

The top ten invaders across South Africa are Syringa (*Melia azedarach*), Pine, Black wattle (*Acacia mearnsii*), Lantana (*Lantana camara*), Rooikrans (*Acacia cyclops*), Port Jackson (*Acacia saligna*), Mesquite (*Prosopis* spp.), Bugweed (*Solanum mauritanium*), *Hakea* and *Opuntia* species (small round-leaved prickly pear) (Marais *et al*. 2001). South Africa comprises 34% of the world's succulent plant species with the genus *Opuntia* having invaded many semi-arid rangelands in South Africa (Musil and Macdonald 2007).

2.2 Woody invasive plant species as bioenergy feedstock

Le Maitre *et al*. (2011) conducted a biomass assessment study to estimate, which IAPs had the greatest potential to yield usable woody biomass (Table1). The data focused on the biomass of IAPs included in the National Invasive Alien Plants Survey (NIAPS) (Kotze *et al*. 2010). In South Africa, especially in rural areas, woody invasive species are mostly used as fuelwood. *Acacia saligna*, *Acacia cyclops*, *Acacia mearnsii*, *Pinus spp.* and *Eucalyptus spp*. are for instance an important source of fuel wood for farmers in the rural parts of the Agulhas plain (de la Fontaine 2013).

Smit (2010) and Munalula and Meincken (2009) evaluated the potential of using important invasive species found in the Western Cape Province, namely *Solanum mauritianum* (Bugweed), *Acacia mearnsii* (Black wattle), *Acacia cyclops* (Rooikrans), *Eucalyptus* spp., *Pinus* spp., and *Hakea* spp. as firewood. They found that *Acacia cyclops*, *Eucalyptus cladocalyx* and *Pinus patula* were the best suitable to be used as fuelwood, adding that the use of *Acacia cyclops* would assist in clearing the existing stocks of the plant, as it is widespread in the Western Cape.

Table 1: The species with the greatest potential woody biomass yield as estimated by (Le Maitre *et al*. 2011)

Species or species group	**Biomass yield**
Acacia cyclops	High
Acacia melanoxylon	High
Acacia mearnsii/ dealbata/ decurrens	High
Acacia saligna	High
Eucalyptus spp.	High
Jacaranda mimosifolia	Moderate
Melia azedarach	Moderate
Pinus spp.	High
Populus spp.	High
Prosopis spp.	Moderate to low
Salix babylonica	Moderate

*The species in bold are those with the greatest potential to yield woody biomass

Mugido *et al.* (2013) conducted a study to determine the financial and economic feasibility of harvesting, extracting, chipping, and transporting invasive alien biomass in a 50 km radius to the EC Biomass (ECB) pellet plant in Port Elizabeth. The outcomes of the study outlined that the harvesting of IAPs for energy production becomes both economically and environmentally viable only if the WfW programme bears a portion of the costs (Mugido *et al*. 2013). In January 2013 the ECB plant shut down, because of a dwindling raw material supply and unfavourable export markets (Argus 2013). Since the primary objective is to clear IAPs, the sustainability of such projects is limited to when the biomass has been cleared (De Lange *et al*. 2012). Therefore, as an exit strategy, the biomass-to-energy technology will need to be relocated or an alternative source of feedstock needs to be found.

Other South African examples of modern biomass energy developments include six wood pellet plants, which have all either closed down or been auctioned off, as a result of a combination of factors including not being able to not reach the optimal efficiency required to make production viable, logistical challenges, unfavourable export market conditions, and failure to secure local markets (Petrie 2014). The BioTech Fuels pellet plant in Howick and the Tsitsikamma sawmill and biomass plant owned by MTO Forestry (Pty) Limited were two of the of the more successful biomass energy developments. Both were privately owned and used local raw material to produce energy.

By 2012 the Howick pellet plant (commissioned in 2006) reached a production capacity of 60 000 tonnes, and in partnership with GAM UK exported 97% of its pellets to the European market (Petrie and Macqueen 2013). Bio Tech experienced logistical challenges associated with sourcing material for pellet production because costs incurred from transport, cleaning and drying were high (Petrie 2014). Further investment was required to increase the plant's production capacity to 72 000 tonnes in order to optimise economies of scale and become profitable (Petrie 2014). In mid-2012 the European market conditions changed and the pellet price (~R1 200 per tonne) was lower than the cost of production (~R1 248 per tonne), which resulted in loss to the Howick plant (Petrie 2014). Within the initial design of the Howick plant there was a 5MW biomass electricity plant aimed to supply the plant and to sell the excess energy to Eskom, but it was never fully commissioned, because no power purchase agreement (PPA) could be secured from Eskom (Petrie and Macqueen 2013). The excess energy should have been fed into the main Eskom grid, but this never materialised, as Eskom failed to facilitate the process (Petrie and Macqueen 2013). As a result, Bio Tech's profitability was further reduced, as they could not subsidise the overall generation costs with grid-supplied electricity. As a last resort Bio Tech explored supplying local pellet stoves for the local market in order to reduce maintenance and logistical costs (Petrie and Macqueen 2013). However, the local market was not yet developed, and in 2013, the project lost its investors resulting in liquidation (Petrie 2014). The 6MW Tsitsikamma biomass plant utilised sawmill waste to generate heat and electricity for the sawmill and neighbouring communities. The failure of these projects highlighted the need for an enabling biomass sector, which supports biomass electricity providers in South Africa. Government policy incentives, subsidies and more support from Eskom could assist in making biomass electricity economically viable (Petrie 2014). In the case of Howick plant there was no local market to serve as back up when export prices (US$165 per tonne) became too high (Petrie and Macqueen 2013). Without subsidies to biomass producers, coal-which is currently the cheapest and most easily accessible energy source will continue to dominate South Africa's energy sector. The question, therefore, is not of the viability of biomass, but rather, how to implement policies that enable the creation of bioenergy markets, thereby contributing to cost reductions associate with logistics.

Neighbouring countries are also experimenting with bioenergy systems. There is for instance great potential for local power generation in Namibia and one of the promising pathways is the conversion of invasive bush encroachment species into wood-fuels, such as charcoal, wood gas for electrification and wood fuel briquettes (Herrmann and Bruntrup 2010). Approximately 26-30 million ha of farmland in Namibia are affected by bush encroachment. This limits the grazing potential of livestock and as a result the livelihoods of about 65 000 households in communal areas and 6 283 commercial farmers are affected (Etango 2010; Hermann and Bruntrup 2010).The economic loss has been estimated at about N$700 million for beef farmers annually. To combat bush encroachment, Namibia is converting invader bush biomass into clean energy. Together with the existing production of charcoal, Namibia unveiled a bioenergy project that generates 250 KW using invader bush as feedstock. The Combating Bush Encroachment for Namibia (CBEND) project was engineered by the Desert Research Foundation of Namibia (Etango 2010) and funded by the European Union in 2010 features a wood gasification plant that produces electricity from invader bush, which is fed into the national grid. Based on favourable levellised cost of power generation, the project was economically viable (1.0-1.1 N$/kWh), mostly because the gasifier is located in one of the most bush infested areas of Namibia, making it a cheap resource for producing energy because of short transport distances (STEAG 2013).

Further away, in India more than 50% of rural communities have no access to electricity and with the economy growing rapidly the demand for electricity is likely to increase with it. Where grid-based electrification is not physically and economically feasible in remote areas, decentralized biomass gasification systems have provided electricity for villagers (MNRE 2010). The key market segments for biomass gasification in India are small/medium industries, the commercial sector and mostly rural communities, which do not have access to electricity. Biomass gasification offered advantages over other energy sources, such as its use of local biomass, high conversion efficiency, guaranteed uninterrupted electricity supply, and its ability to be used over a wide range of application (MNRE 2010). This resulted in the per unit cost of biomass gasification being favourable over other alternative energy sources. Although the per unit cost to generate electricity from biomass gasification was lowest among renewables (MNRE 2010), it was more expensive than coal-based electricity from the national grid (Kumar *et al*. 2011). Case studies of biomass gasification for village electrification in India are well documented. The Husk Power System (HPS) is one of the more successful rural electrification systems in India. The HPS uses rice husks as feedstock and generates enough electricity to cater for almost 22 villages in the rice belt of India (UN India 2011). In comparison South Africa is heavily reliant on a coal-based centralised grid for electricity production (Petrie and Macqueen 2013). Decentralised off-grid biomass plants cannot compete with Eskom's electricity generated from cheap coal.

Liao *et al* (2013) investigated the potential of using invasive plant species as feedstock for value-added products, such as bio-char and bioenergy via pyrolysis and studied the potential of Brazilian Pepper (*Schinus terebithifoluis*) and Air Potato (*Dioscorea bulbifera*), which are aggressive invasive alien plants in the south-eastern United States. Brazilian Pepper and Air Potato yields were compared to that of water oak and sugarcane at three pyrolysis temperatures. Results showed that BP and AP could be used as feedstock for value-added products, as their bio-char and bioenergy yields did not differ much to that of traditional biomass feedstock (Liao *et al*. 2013).

2.3 Non-woody invasive plant species as bioenergy feedstock

While most studies deal with the bioenergy potential of woody species as illustrated in section 2.2, limited literature is available in South Africa on the use of non-woody IAPs. Some of the widespread non-woody IAPs found in South Africa include Water hyacinth (*Eichhornia crassipes*), Bugweed (*Solanium mauritanium*), Triffid weed (*Chromoleana odorata)*, *Lantana camara*, Giant reed (*Arundo donax*), Queen of the night (*Cereus jamacaru*), Old man salt bush (*Atriplex nummularia*), Englantine (*Rosa rubiginosa*), *Opuntia spp*, *Agave spp*., and Mauritius thorn (*Caesalpinia decapetala*) (Table 2).

Table 2: Important non-woody IAPs and their impact on ecosystem services in five biomes in South Africa (adapted from van Wilgen *et al*. 2007)

Prominent IAP species	**Accessibility of invasive plants**	**Estimated impact on biodiversity**
Arundo donax (giant reed)	Easy to difficult: riparian, widespread	High
Agave Americana (american agave)	Easy: inland plains	Moderate
Atriplex nummularia (old man saltbush)	Easy: inlands	Moderate
Caesalpinia decapetala (Mauritius thorn)	Difficult: riparian, forest, montane areas	Moderate
Cestrum laevigatum (inkberry)	Easy to difficult: savanna, coastal	Moderate
Chromoleana odorata (triffid weed)	Easy to difficult: savanna	High
Einchornia crassipes (water hyacinth)	Difficult: watercourses (lakes, dams, rivers)	High
Lantana camara (lantana)	Easy to difficult: widespread	High
Senna didymobotrya (peanut butter cassia)	Easy to difficult: savanna, forest	Moderate
Solanum mauritianum (bugweed)	Easy to difficult: widespread	Moderate

Van Wilgen *et al*. (2007) rated the impacts on biodiversity as high or moderate if the impact followed a similar disturbance pattern to that of a plantation or degraded area. *Arundo donax* has a high impact on biodiversity because it produces bamboo-like stems and forms fairly dense stands, which can reach 3-4 m in height and have a fast regrowth rate (Le Maitre *et al*. 2011). *Arundo donax* also affects surface water runoff in riparian areas of grassland, savannah, and the fynbos biomes (van Wilgen *et al*. 2007). *Chromoleana odorata* and *Lantana camara* are on the list of top 10 invaders in South Africa, and are prominent invasive species in the savanna, the Indian Ocean coastal belt and forest. Water hyacinth (*Einchornia crassipes*) is one of the most widespread and damaging floating aquatic weeds in South Africa (Musil and Macdonald 2007; Byrne *et al*. 2010) and its populations are increasing because of the absence of natural enemies in new habitats (Lu *et al*. 2010).

2.4 Factors affecting the biomass supply for bioenergy production

The supply chain model allows us to understand the cost implications for biomass fuels better, as well as to make comparisons to the cost of different fuel supply systems. A variety of factors, including economic, environmental, social, technical and policy factors affect the biomass value chain (Gan and Mayfield 2007) and, given the close interaction between feedstock production and energy conversion, the entire IAP bioenergy value chain needs to be optimised in order to achieve overall efficiency (Gan and Mayfield 2007). The factors that affect bioenergy value chain include the choice of feedstock and feedstock availability, and supply chain activities, including harvesting, pre-processing (comminution and drying), transport, chosen conversion technology, timescale, economies of scale, capital investment, costs of operations and the overall economic feasibility of operations. These factors are discussed in more detail in the following paragraphs.

2.5 Biomass supply chain

Generation of bioenergy entails a series of processing activities namely: harvesting, in-field extraction, pre-processing, storage and road transport to the power plant (Allen *et al*. 1998; Rentizelas *et al*. 2009). Harvesting and extraction refer to obtaining the biomass from the source and delivering it to be pre-processed. Pre-processing includes processes (e.g. milling, chipping, grinding) that prepare the biomass for transportation to the conversion plant. Transportation involves moving biomass from the source to the plant where it will be processed into different products, including electricity. In the case of this study all the biomass is intended for electricity generation. An illustration of the bioenergy value chain assumed in this study, from harvesting to the supply to plant is shown in Figure 2. Logistic operations have a big impact on the profitability of bioenergy production systems. Rentizelas *et al*. (2009) attributed the distinctive characteristics of biomass supply chains as the main contributors to the high costs of biomass utilization. These include seasonality of biomass, which affects the security of feedstock supply, low-density of biomass material, which increases transport costs and the form in which biomass is procured (chips, unconsolidated material, etc.) which may require different transport and handling equipment.

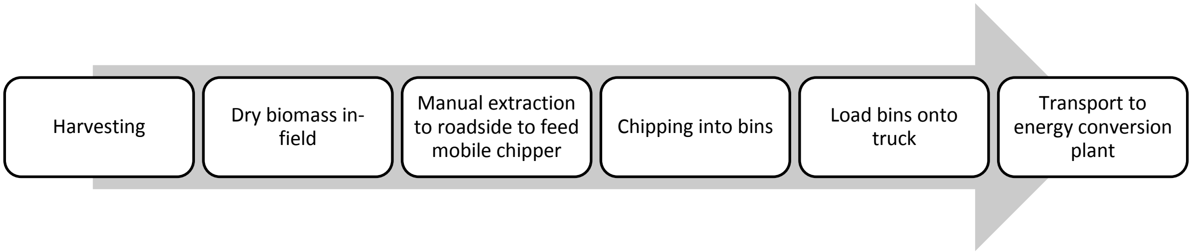

Figure 2: The bioenergy supply chain addressed in this study, from harvesting to the delivery to an energy conversion plant.

A major barrier to the widespread use of bioenergy is the low energy density of biomass, which is significantly lower than that of fossils fuels. This means that more fuel is required to produce the same amount of energy, which results in increased transport, storage, and utilisation costs. Another characteristic of most biomass is its seasonal availability. Biomass needs to be stored so that the power plant can be supplied continuously. Although there are cost-effective ways of storing biomass, there are risks associated with cheaper storage methods. When biomass with high moisture is stored prior to drying it can create a fire hazard and the piles can even self-ignite. Prolonged storage also increases the risk of biomass degradation and material loss (Rentizelas *et al*. 2009).

2.5.1 Feedstock selection, supply and availability

Although there is potential for biomass to be used for electricity generation, there are accompanying risks. Sustainability of fuel supply and the cost of biomass are some of the risks associated with biomass electricity production (Mugido *et al*. 2013). Access to the biomass is essential to providing a sustainable supply of feedstock over time. Creating a secure supply of raw material over time is important for bioenergy investors as they have to re-coup their investment (Invest ABI Alien Clearing report draft, 2015). Furthermore, the intrinsic characteristics of biomass, such as its geographical distribution over the landscape contribute to the costs of harvesting and transport (Keefe *et al*. 2014).

Producing electricity from biomass is more expensive when compared with coal because of the current logistical costs associated with biomass fuel supply (Allen *et al*. 1998; Caputo *et al*. 2005; Mugido *et al*. 2013). Although biomass power plants are smaller in scale in comparison with coal-fired power stations, the low bulk density nature of biomass means that significant quantities of biomass fuel are required, which increases the volume that needs to be transported (Allen *et al*. 1998; Schroeder *et al*. 2007). This further increases costs of transport, storage, processing, loading and unloading (Allen *et al*. 1998). Therefore, it is important to ensure the supply of biomass is sustainable to decrease the costs further down the supply chain.

The choice of biomass feedstock is important for bioenergy production as it influences the fuel characteristics for energy conversion. The chosen biomass needs to be suitable to use, as the choice of appropriate conversion technology is dependent on the type of biomass feedstock (Caputo *et al*. 2005; ECN 2014). Biomass properties, such as moisture content, ash content, proportion of fixed carbon and volatiles are all species dependent. For thermochemical conversion techniques, such as combustion, pyrolysis, or gasification, biomass with low ash, moisture and volatile content is preferred, whereas biological conversions, such as anaerobic digestion can handle high moisture content biomass and the ash- and volatile content are less important. The energy content of the feedstock determines the maximum possible electricity output.

2.5.2 Harvesting and extraction

Harvesting, chipping and transport costs are very site specific. The harvesting approach is dependent on factors, such as type and density of feedstock on the land, slope, labour costs, equipment and fuel costs (DEA 2015). The cost elements associated with harvesting include capital costs of machinery, terrain conditions and operator productivity (Kitenge 2011). Harvesting of woody biomass can be done manually with chainsaws or with mechanised systems (e.g. harvesters, feller-bunchers) (ICFR 2013), the latter being the most commonly used harvest systems for removing wood from forest plantations (Ashton *et al*. 2007). However, these highly mechanised harvesting systems are mainly suitable for higher-grade timber covering large areas. Small-scale timber harvesting systems are commonly used to harvest less valuable timber, as for example, for bioenergy products (Ashton *et al*. 2007). Generally, the manual method (felling axes, chainsaws and brush cutters) is the most suitable to harvest invader bush. In the study by Mugido *et al*. (2013), chainsaws and brush cutters were used to fell the woody IAPs and they are also regarded as the most suitable harvesting method in this project, as they are used by WfW harvesting teams to clear invasive plants, depending on the size of the plant. Although these methods are very labour intensive, they have low investment costs, as well as minimal environmental impacts (STEAG 2013).

Extraction involves two stages: first stacking branches in-field/roadside and then dragging the branches from the field to the chipper (Mugido *et al*. 2013). Manual extraction is the commonly used method for operations from invasive species, bush encroachment and woodland species (STEAG 2013).

2.5.3 Biomass pre-treatment: Drying and storage

Freshly harvested biomass can contain up to 40 to 60% moisture. Post-harvest handling and storage conditions have an effect on the amount of moisture found in woody biomass (Jackson *et al*. 2007). Therefore, drying of biomass is essential to improve the handling efficiency, reduce transport weight, increase heating value and to decrease biological degradation (Gold and Seuring 2011). Biomass can either be air-dried in field, at the roadside, or the processing plant, or kiln dried, which is costly. The most cost effective drying method is transpiration drying (drying in open air); however, the rate depends factors, such as the ambient temperature, humidity and the season (Jackson *et al*. 2007; Gold and Seuring 2011; von Doderer 2012). In the study by Mugido *et al*. (2013) woody IAPs were stacked and left in-field to dry for three to four weeks after being harvested, which could also be done for non-woody IAPs. The preferred drying method for comminuted biomass is (solar) kiln drying, as it prevents fungal and bacterial degradation. An important consideration for transport is that drying decreases the weight of the biomass and reduces the fuel consumption and emissions (Roberts 2010). According to von Doderer (2012), irrespective of whether the biomass was dried in-field or not, it may still have to undergo additional thermal drying in order to meet the specific moisture level requirements of the conversion technologies.

Biomass storage is another important consideration in the value chain. Some biomass resources need to be stored to ensure an all year round supply of energy, because they are seasonally available (Ashton *et al*. 2007; Rentizelas *et al*. 2009; IEA, 2012). Biomass can be stored in different forms (e.g. solid or chipped) at different locations (in field, roadside, terminal, plant). The type and duration of storage, volume to be stored (Gold and Seuring 2011) and height of storage piles (Jirjis 2005) have an effect on the overall value chain costs and on the quality of the biomass. Although the in field storage is the most cost effective, it can result in physical, chemical and biological damage to the biomass (Rentizelas *et al*. 2009). The danger of storing chips in piles is self-ignition, as fungal and bacterial degradation increases the temperature in the pile. If this temperature gets high enough the pile can self-ignite. Another consideration is storage length, as it could lead to the loss of turpentine, an extractive that protects the wood from microbial attack. The loss of turpentine increases possibility of biological degradation. Thus, there needs to be careful planning of storage location and method.

2.5.4 Biomass pre-treatment: Comminution and densification

It is necessary for biomass to be reduced in size (comminuted) as it comes in different sizes and shapes. Pre-processing can improve the quality and increase the energy density of biomass (ECN 2014). A uniform particle size is beneficial for transport costs, as it increases the loading (or loose) density of the biomass, resulting in more material being transported per unit distance (Zafar 2013). Thermochemical conversion technologies, such as combustion, gasification and pyrolysis have specific requirements for the feedstock properties (von Doderer 2012). The form of the biomass can determine the capital and running costs of the chosen conversion technology, as it affects the design and requirements of the entire energy conversion chain (Rentizelas *et al*. 2009; Pantaleo and Shah 2013). Most reactors require a uniform particle size, which affects the reaction rate. For small particles the energy density generally increases with decreasing particle size, because the reactive surface area increases proportionally. The ease of processability of the feedstock is important, as it determines what additional costs are required for pre-treatment before conversion (Zafar 2013).

Comminution can take place in field, at roadside, at a terminal, or at the conversion plant. According to Svanberg (2013) when comminution takes place in the early stages of the supply chain (e.g. at roadside), transportation is made more efficient. However, to prevent fungal degradation, the biomass should be proceed further preferably within 14 days after comminution (Jackson *et al*. 2007). Technologies for comminution include chipping, milling, and subsequent compression into uniform sized pellets or briquettes. Chippers are the most widely us biomass size-reduction machines for woody biomass, as they are well integrated into existing harvesting systems (Jackson *et al*. 2007). Pre-processing such as chipping and drying ensures that the biomass has the suitable moisture content and particle size for the conversion technology to be used. When it comes to transporting low-density chips it generally is only economically feasible to transport unprocessed biomass less than approximately 200 km (Clarke and Preto 2011) because with long distance transportation the transport costs tend to increase.

Wood chips can be further milled and compressed into briquettes and pellets via a process called densification. It is a way to increase the energy density and overcome handling difficulties (Clarke and Preto 2011). Another advantage of briquettes and pellets is their uniformity in particle size and physical and chemical properties, which is a required by most reactors. Biomass densification is a physical process that involves compressing large volumes of low density biomass into pellets or briquettes with a higher mass and energy density. They have better and more consistent thermal and physical properties allowing for more complete combustion, which results in greater conversion efficiency. The main advantages of compressing biomass are the decrease in transport costs and easier handling and storage especially in industrial settings (Sustainable Bioenergy Development in UEMOA Member Countries, 2008:53).

2.5.5 Biomass transport

After harvesting, drying and chipping the biomass needs to be transported to a conversion plant for further processing. According to ICFR (2013), road transport constitutes one third of the total cost of the biomass fuel. Truck transport is the preferred method of transport for distances less than 100 km (Allen *et al*. 1998; Roberts 2010). The cost factors associated with truck transportation include fuel costs, costs associated with loading/unloading , number of trips, duration of downtime, distance, moisture content and truck payload (Shuttleworth and Ackerman 2009; Roberts 2010; Kitenge 2011). The transport costs of biomass are the biggest cost factor limiting the growth of the industry (ICFR 2013), because biomass is bulky and has a lower energy density in comparison with fossil fuels (Searcy *et al*. 2007; Clarke and Preto 2011). Furthermore, haulage distances to the processing plant limit the profitability of bioenergy enterprises. The preferred average moisture content for secondary transport in the industry is 40% (von Doderer 2012). High moisture levels in biomass contribute to the mass of the load, but not to its value, thereby resulting in higher fuel consumption and increase in utilization costs (ICFR 2013). Densification of biomass can reduce transportation costs, as it increases the dry matter bulk density (Clarke and Preto 2011). Important to note is that biomass is most economically feasible when used close to the source.

2.6 Bioenergy conversion processes

Biomass refers to any organic material that is derived from plants (McKendry 2002; Viglasky *et al*. 2009). Biomass resources include wood, agricultural crops, municipal solid waste, sugar, etc. (Caputo *et al*. 2005). There are several conversion routes that transform biomass into energy and other valuable products. Bioenergy includes heat, electricity and liquid bio-fuels and the main use of bioenergy in the world is for heat production (Viglasky *et al*. 2009).

Electricity and co-generation of heat and power obtained from the combustion of biomass, or biogas from anaerobic digestion are increasing worldwide. Liquid bio-fuels - produced by fermentation - include ethanol for use in gasoline engines and bio-diesel – obtained through pyrolysis - which can be used in blends with conventional diesel (Viglasky *et al*. 2009).

2.6.1 Conversion technologies

Biomass has traditionally been used for heating in open fireplaces and stoves in developing countries (Meincken and Munalula 2009), but with technological developments in the field of biomass energy conversion there has been a shift to modern biomass uses in efficient boilers and furnaces (Demirbas 2001; IRENA 2014). Bioenergy conversion technologies are grouped into thermochemical (combustion, gasification, pyrolysis, liquefaction) and bio-chemical (fermentation, anaerobic digestion) (McKendry 2002; Görgens *et al*. 2014). By means of thermo-chemical and bio-chemical processes biomass can be converted into intermediate bioenergy products in the forms of solid (e.g. charcoal), gas (e.g. methane and hydrogen) and liquid fuels (e.g. bio-oils, methanol and ethanol) (ICFR 2013; Görgens *et al*. 2014). These fuels can be used to produce heat and electricity, transportation fuels, and various non-energy products (e.g. bio char) (Görgens *et al*. 2014). Factors affecting the choice conversion process are the type of biomass feedstock, the product required (e.g. electricity or heat), the scale of installation and technology maturity (Potgieter 2011).

This study only assessed the potential of non-woody IAPs for electricity generation, with the main focus on thermochemical conversion. Although some of the species might be suitable for bio-chemical conversion, a detailed overview of biochemical pathways is beyond the scope of this study.

2.6.1.1 Thermochemical conversion technologies

Thermo-chemical conversion technologies require low moisture content (<30%) biomass feedstock, while bio-chemical conversion can utilise biomass feedstock with high moisture content (McKendry 2002). The biomass conversion options potentially suitable for the conversion of non-woody IAPs are combustion, pyrolysis, gasification and anaerobic digestion. The conversion routes are used to convert various biomass types into different energy products, as displayed in Figure 3.

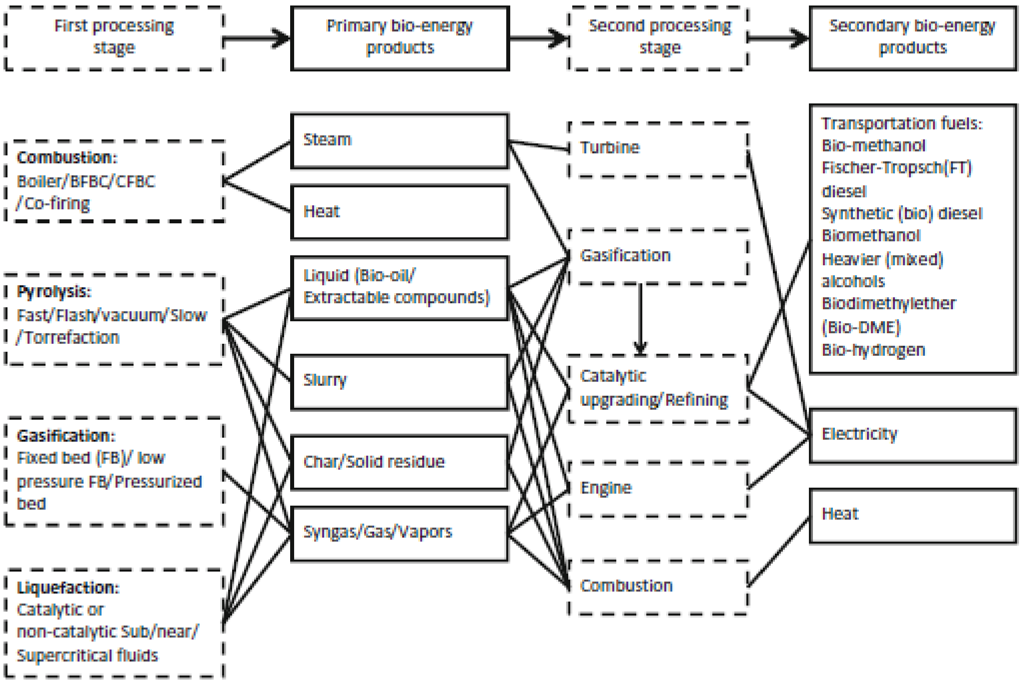

Figure 3: Thermo-chemical biomass conversion processes for biofuels (Görgens *et al*. 2014).

Combustion – or the burning in the presence of oxygen of biomass accounts for over 90% of the power generated from biomass (IRENA 2012). Combustion is also the most basic conversion technology to convert biomass into energy (Cutz *et al*. 2016). In Africa where biomass is used as the main energy resource, combustion in its simplest form has been widely used for cooking and heating for centuries (Meincken 2011). Generating electricity from biomass combustion is a two-step process: the biomass is burnt in a furnace and the resulting heat is used to produce steam, which is passed through a steam turbine, where the thermal energy is converted into mechanical energy that is used to generate electricity through a generator (IRENA 2012). Direct combustion biomass power plants typically use fluidized bed boilers and steam turbines to generate heat and power (Ontario Federation of Agriculture 2012). Large-scale biomass combustion plants that convert biomass into heat and electricity are commercially the most proven power generating reactors and are the most reliable and cost effective method of providing electricity (IEA 2012; NamPower 2012). Biomass combustion is versatile in that it allows for a wide range of feedstock moisture content. Modern biomass combustion applications include centralized heating and power (CHP) plants used in housing, manufacturing and industrial settings (ECN 2014).

Gasification is a process where biomass is burnt in an oxygen starved atmosphere, which maximises the emission of volatile gases that can be captured and stored. The gas contains enough energy to generate electricity and heat when burnt at a later stage. Depending on the amount of oxygen allowed into the process, different gaseous products are obtained. The collected producer gas consists of carbon monoxide (CO), hydrogen (H) and methane (CH_4), which are flammable and can be burnt directly or stored to later fuel gas turbines, to produce electricity (Goyal 2006; Meincken 2011). Gasification is a highly versatile process, as a variety of biomass, including wood pellets and chips and waste-derived feedstock, such as forest residue, municipal waste and sewage sludge can be gasified (ECN 2014). The reactors typically used in gasification technologies are fixed bed gasifiers (updraft, down draft, cross-draft) fluidised bed gasifiers (bubbling bed, fluidised bed, circulating fluidised bed), entrained flow gasifiers, multi-bed and plasma gasifiers (IEA 2004; Görgens *et al*. 2014; IEA 2016). Gasification is more efficient and attractive at smaller scale (less than 1 MW) for off-grid applications. However, it is still an emerging technology and is less competitive than combustion-steam systems, because it is characterised by higher operational and capital costs (McKendry 2002; Pierce 2015).

Pyrolysis is the thermal decomposition of biomass into a different fuel types in the absence of oxygen at high temperatures (350°C-600°C) (Demirbas 2000; McKendry 2002; Bridgwater 2012). Pyrolysis produces a blend of hydrocarbon rich gases, liquids and solids that can be collected separately and used as biofuel (bio-oil), charcoal and syngas (Demirbas 2000; Bridgwater *et al*. 2002). Pyrolysis process types include fast pyrolysis, slow pyrolysis, vacuum pyrolysis, pressurized pyrolysis, flash pyrolysis and torrefaction pyrolysis (Görgens *et al*. 2014). Each process yields a different ratio of solid, liquid and gaseous components depending on the reactor conditions (temperature, vapour residence time and heating rate) in the pyrolysis reactor (Demirbas 2000; Görgens *et al*. 2014). Fast pyrolysis is the rapid heating of biomass (about 300°C/min), which produces high yields of bio-oil (up to 75 wt%) (Bridgwater 2006). The liquid bio-oil needs to be treated and upgraded to be processed into bio-diesel, which can be used in engines and turbines (Demirbas 2000). Flash pyrolysis of biomass occurs at very high heating rates (higher than fast pyrolysis) in a short reaction time of only seconds (Goyal *et al*. 2008). Slow pyrolysis produces predominantly charcoal and little gas and liquid (Goyal *et al*. 2008). Vacuum pyrolysis is similar to slow pyrolysis, but produces better quality of char and liquid, as it takes place under vacuum, which allows for removal of gaseous vapours from the reaction zone (Goyal *et al*. 2008; Görgens *et al*. 2014). Pyrolysis reactors include fixed bed, moving bed, fluidized and suspended bed reactor designs (Goyal *et al*. 2008). Torrefaction is a mild pyrolysis process at relatively low temperatures (200-300°C), which is used to upgrade the biomass quality by removing moisture and volatiles (Görgens *et al*. 2014). The torrefied product is dry, energy-dense biomass with coal-like properties that can be used for combustion and gasification applications (Eskom 2014).

Liquefaction or thermal depolymerisation is a non-pyrolytic process that converts biomass into a stable liquid hydrocarbon by subjecting it to low temperatures and high atmospheric pressures (McKendry 2002; Görgens *et al*. 2014). In essence, liquefaction is a process, which mimics nature's production of fossil oil, but in a shorter time span (Cassidy and Ashton 2007). Although direct liquefaction has been successful in producing liquid oil, pyrolysis is favoured as a conversion process, because liquefaction requires complicated and expensive reactors and fuel-feeding systems (McKendry 2002). Furthermore, Görgens *et al*. (2014) stated that liquefaction technologies have not been successfully commercialised, due to technical difficulties when scaling up from batch reactors to continuously processing systems.

2.6.1.2 Bio-chemical Conversion Processes

Bio-chemical conversion processes use biological and chemical processes to produce bioenergy in the liquid (i.e. bioethanol) or gaseous (i.e. biogas) form (Cassidy and Ashton 2007). These bioenergy products can potentially substitute conventional combustible fuels used for transport and electricity generation (Görgens *et al*. 2014). Fermentation and anaerobic digestion are particularly suitable for materials with high moisture content, as drying is not required (Bridgwater 2006).

Anaerobic digestion (AD) is a natural process, where organic material is broken down by bacteria in the absence of oxygen (ECN 2014). For anaerobic digestion feedstock with high moisture content is preferred (Caputo *et al*. 2005; Meincken and Tyhoda 2014). The process is carried out in an air tight chamber that is fed with water and organic biomass, which can be raw sewage, food waste or plant matter. This process produces biogas rich in methane and carbon dioxide, which can be captured, stored, and burned later for heating, cooking and even in internal combustion engines to generate electricity. In developing countries such as India, Nepal, South Korea, Brazil, and Thailand small-scale AD technologies are used to produce biogas (UNF 2008).

Fermentation is a process that produces biofuels such as ethanol, butanol, butanediol and various other alcohol mixtures using enzymes and other micro-organisms (Görgens *et al*. 2014). Technologies, which produce ethanol are more mature and widely used (Görgens *et al*. 2014). Ethanol production is typically a multi- step process: first the cellulose and hemicelluloses in biomass are hydrolysed to sugars by enzymes in warm fermented tanks, then the enzymes break down the sugar to form methanol and ethanol, where the ethanol content is around 10-15%. This diluted alcohol is distilled to remove impurities and excess water and ethanol is extracted (Demirbas 2001). Various biomass materials, which contain sugars, starch or cellulose have been used to produce ethanol with sugar cane being the most widely used feedstock (Demirbas 2001). A negative aspect of fermentation is the low overall efficiency, which can be attributed to energy losses in the distillation stage of extracting ethanol (Demirbas 2001; Bridgwater 2006).

2.6.2 Cogeneration Power plants

Cogeneration or combined heat and power (CHP) refers to the integrated production of electricity and heat in one technological process (Demirbas 2007). Modern CHP plants based on biomass combustion, and integrated gasification/gas turbine (BIG/GT) have undergone intensive development over the years (ICFR 2013; Görgens *et al*. 2014; IEA 2016). Combustion boiler-steam turbine systems use steam to turn the turbines and drive generators that produce electricity (Demirbas 2007) and similarly BIG/GT combust the gases produced through gasification, pyrolysis and anaerobic digestion to produce electricity and heat (Görgens *et al*. 2014). According to ICFR (2013), these are the only two well-established conversion technologies, both overseas as well as in South Africa. Demirbas (2007) stated that the future of biomass electricity generation lies in biomass integrated BIG/GT technologies, because they deliver high conversion efficiencies. IEA (2016) reported that over 200 commercial CHP small-scale gasification facilities exist worldwide. CHP technologies are often installed in industrial setups (pulp and paper, steel, or processing industries), or for communal space and water heating in buildings, directly or through a district heating networks space heating (Demirbas 2007; IRENA 2012; IEA 2016).

2.6.2.1 Prime mover technologies

Prime mover technologies are machines that convert energy from source energy into electricity or shaft power. All biomass-to-electricity systems have prime mover technologies. CHP systems consist of two main components: the **energy conversion system,** where biomass is converted into steam or producer gas, and an **electricity and heat generation system** that generates electricity and heat from steam or gas (Garcia *et al*. 2016). The components of a CHP system include a prime mover (heat engine that drives the CHP system), the generator, the heat collection system and the electrical interconnection (Garcia *et al*. 2016; Demirbas 2007). The prime movers are steam turbines, reciprocating internal combustion engines, gas turbines and stirling engines. These are capable of burning a wide range of fuels, including natural gas, coal and oil, to produce electrical or mechanical energy (Zafar 2015).

Steam turbines are mature, proven prime movers that generate electricity from the steam produced by combustion of solid and gaseous fuels (Görgens *et al*. 2014; Zafar 2015). The steam turbine operates on a closed-circuit process (i.e. the fuel and thermal cycle are separate), enabling the use of fuel containing ash and contaminants (Garcia *et al*. 2016). In CHP plants, the steam moving the turbines is converted into electric power and remaining thermal heat that can be used for heating water (Görgens *et al*. 2014). The system conversion efficiency can be as high as 55%, depending on steam parameters.

A *stirling engine* is another prime mover that utilizes both solid and gaseous biomass fuels. It uses high temperature heat to convert mechanical energy into electrical energy. Stirling engines are the only heat engines that use combustion to provide electricity (McKendry 2002).

Gas turbines, also known as combustion turbines burn high-energy fuels (i.e. gas) to either generate electricity only, or electricity and heat (Garcia *et al*. 2016). Purification of gas fuels prior to combustion is required, as contaminated fuels damage the turbine blades. The efficiency of a gas turbine is typically around 30%.

Internal combustion engines (ICE) are widely used to power small electricity generators. They are reliable and are able to reach good efficiencies under partial load efficiency. Like gas turbines, this type of engine requires clean fuels.

2.6.3 Technology maturity for commercial use

The degree of technology maturity needs to be considered when selecting suitable conversion technologies for biomass into bioenergy products (Görgens *et al*. 2014). Many commercially proven power generation technologies that are suited to biomass fuels exist (IRENA 2012). The development stages and technology capabilities of combustion, gasification, pyrolysis, anaerobic digestion and fermentation are discussed

Direct combustion systems that generate energy for heat, electricity and CHP (combined heat and electricity) from biomass are a mature, technically and commercially proven technology (IEA 2012; IRENA 2012; Görgens *et al*. 2014). They have been proven to work with a wide range of fuels. IRENA (2012) reported that over 90% of the energy produced from biomass worldwide is generated via combustion. In Europe especially, CHP are widely used for small and large-scale commercial applications (Ontario Federation of Agriculture 2012). Co-firing of biomass with coal to generate electricity and heat is becoming increasingly common. Electric efficiency of biomass co-firing plants is higher than dedicated combustion plants (IRENA 2012). Low-rate co-firing systems are a mature technology (IRENA 2012), but very few large-scale co-firing applications exist (Görgens *et al*. 2014).

Biomass gasification technologies are commercially available around the world, but key challenges of biomass processing, improving biomass flexibility, gas cleaning, pre-treatment need more research and development before their commercial use can be promoted (IRENA 2012; Görgens et al. 2014). In 2012, IRENA reported that only around 373 MW_{th} of installed large-scale capacity gasification technologies were in use in 2010, with just two additional projects totalling 29 MW_{th} planned for the period to 2016. In South Africa and Malaysia, the Fischer- Tropsch synthesis, using syngas to produce liquid fuels has been widely used commercially (Görgens *et al*. 2014).

Pyrolysis technologies are in commercial operation without serious reliability issues. According to Görgens *et al*. (2014) all the different pyrolysis processes are mature technologies. A number of slow pyrolysis technologies that produce charcoal and bio-char are commercially available (Biogreen Energy, Enecon, Bioenergy Ltd., etc.) (Görgens *et al*. 2014).

Anaerobic digestion is a commercially proven technology and is widely used for converting high moisture content organic waste into biogas (McKendry 2002; Görgens *et al*. 2014). However, research and development needs to address issues of low conversion efficiency, which could stem from inadequate pre-treatment applied to biomass (Görgens *et al*. 2014).

Ethanol produced from lignocellulose via *fermentation* has great potential as an alternative for liquid transportation fuel (Wyman 2007). Commercial cellulosic ethanol plants exist in Europe (Beta Renewables), Brazil (Alagoas), USA (KL Energy Corporation, Abengoa Bioenergy, etc.), and Canada (VANERCO). There is ongoing research based on pre-treatment processes, suitable feedstock sources, and enzyme development for cellulosic ethanol technologies.

2.7 Economic feasibility

2.7.1 Impact of logistics on profitability

The choice of location for a bioenergy plant is determined by the availability and logistics of the IAP biomass (ECN 2014). The distance between the conversion plant and the feedstock source should be as short as possible (ECN 2014), as long transport distances and associated costs have a negative impact on the economics of the logistics system (ECN 2014). Invasive plants are often distributed in patches and in many cases the biomass will need to be collected from different sites and it will have to be pre-processed for easier transport, before it can be moved to a processing plant. It therefore, makes economic sense to locate the plant close to the biomass source to reduce transportation costs (Zafar 2013).

According to Allen *et al*. (1998) and Mugido *et al*. (2013) the price to produce electricity from biomass compares unfavourably to that of coal. Most biomass energy projects have a high transportation element, because woody and non-woody biomass has a lower energy density when compared to fossil fuels (Searcy *et al*. 2007; Ashton *et al*. 2007). Biomass supply chains deal with low density materials and as such incur increased transportation and handling costs. Therefore, it becomes very important to plan the most economically feasible distances and routes when transporting invasive plant materials. Factors, such as the average transport distance, travel speed and biomass density influence the choice of transportation vehicle. Transporting chips (although they have a higher energy density than unconsolidated material) means that less volume can be transported, because of its relatively low bulk density (in comparison with fossil fuel) and calorific value (Allen *et al*. 1998).

Furthermore, the clearing of IAPs implies the diminishing of stock over time, and thus decommissioning and relocation, or change of feedstock is required as an exit strategy for the biomass-to bioenergy technology when the IAPs become depleted (De Lange 2011). In the prefeasibility stage it also needs to be determined whether or not there is a supplier readily available with the appropriate technology (ECN 2014).

Determining economic viability is relevant to any project that is profit driven (ECN 2014). Bioenergy entrepreneurs who invest in such projects seek to make profit, thus an economic analysis of costs and the cost impact of the main logistic variables helps to give them confidence about the sustainability of biomass to power projects. An economic analysis usually involves collecting information of costs of the different value chain components and applying a financial decision making tool (ICFR 2013; ECN 2014). The most relevant cost information required for financial analysis are capital costs which include financing costs of the project; operation and maintenance costs, cost of feedstock, transport, and biomass conversion (ECN 2014; Petrie 2015). The following section evaluates the impact of important logistic variables, such as feedstock costs with its associated drying and storage costs and the biomass transport costs on the viability of biomass use for various electricity production. This study focused on the costs to supply biomass to a conversion plant only and not the actual costs of electricity generation, as the evaluation of the various different technologies and reactors would be beyond the scope of this study. Fuel costs for transport are an important factor, as invasive plants often grow in areas that are not easily accessible (Petrie 2015). The scale of the operation is also important when dealing with potential electricity generation, as there are significant capital cost savings with highly efficient large-scale generation units (IEA 2012).

2.7.1.1 Feedstock costs

Feedstock costs include the biomass price (paid to a landowner) and the harvesting cost (felling, extraction, chipping and handling). Various biomass feedstock can be used for energy generation, including agricultural waste, municipal waste, forest residues, invasive plants, wood pellets, wood chips, etc. Very little cost information on biomass supply in developing countries exists, since large-scale commercial bioenergy systems are not commercialised (IEA 2012). According to IRENA (2012), feedstock supply costs account for 40-50% of the total cost of electricity generated. The costs to deliver biomass for energy application are higher than coal (IEA Bioenergy 2006; IEA 2012). Agricultural waste is typically the lowest cost feedstock type (IRENA 2012). Feedstock costs for cellulosic ethanol account for one third of the value chain costs for commercial commodity products (Wyaman 2007). The economic feasibility assessment in this study did not include the biomass price, as the IAPs need to be cleared and therefore do not incur buying costs

Harvesting is the next step in the value chain. The objective of this study was to assess non-woody IAPs as a source of biomass for electricity generation. The main constraint associated with the harvesting of IAPs in South Africa is the difficulty to access them, because unlike commercial (plantation) trees, IAPs grow neither in consolidated areas, nor in straight rows (Eco-Invest ABI 2015). Invasive plants are often scattered across the landscape and thus non standardised systems need to be applied. Another characteristic of invasive species infested areas is that densities of biomass per hectare vary substantially, and the plants are not all of the same size and height (Eco-Invest ABI 2015). There is a lack of tried and tested commercial systems in South Africa that are tailored for the harvesting of IAPs for bioenergy purposes. There is no single most productive biomass harvesting system and different conditions will favour different systems. The key is to select the correct equipment for the specific application and make sure to take into consideration all downstream effects the use of the equipment will have.

Pre-processing can involve drying, comminution and storage in the case of heat and electricity generation, or chemical pre-treatment for cellulosic ethanol production. The types of biomass feedstock and the initial moisture content influence the costs of drying. Systems for storing and handling biomass have to be bigger and therefore more expensive than the fossil fuel equivalents (IEA 2012). The capital costs for pre-processing and handling of heat and power generation systems represent 6%- 20% of the total investment costs (IRENA 2012). Furthermore, economies of scale exist in biomass feedstock preparation and handling, with capital costs being lower for systems with higher throughput (IRENA 2012). According to Wyaman (2007), pre-treatment costs make up 67% of the total costs for cellulosic ethanol.

2.7.1.2 Costs of biomass transport to energy plant

Biomass, by its nature, is often found in remote areas far from the place where the energy will be consumed (Searcy *et al*. 2007). There is a choice to either transport the biomass to a conversion plant, or transmit the energy produced from a local biomass plant to the energy consumer (Searcy *et al*. 2007). Transportation is a big cost contributor in any energy project. According to Searcy *et al*. (2007) transportation costs components can be divided into distance variable costs (DVC) and distance fixed costs (DFC). DVCs are dependent on transport distance, e.g. truck transport cost “per tonne kilometre”. This is why local consumption of biomass fuel is more feasible because it helps to reduce the transport component of fuel costs.

DFCs on the other hand are not distance dependent, but are rather affected by the type of biomass and truck operating costs (e.g. loading and unloading costs, maintenance costs) (Searcy *et al*. 2007). The true determinant of transport costs is the payload. Payload is determined by mass or volume, and since biomass has low density, payload is often reached before maximum mass allowance. Biomass transportation costs vary with the amount of biomass (in t) and road limits (Searcy et al. 2007). In the study by Johansson *et al.* (2006) transporting fuel chips for long distances in road transport was found to be more expensive than transporting bundles. With bundling of residues, the use of conventional and efficient equipment decreases the costs of forwarding, road transport and comminution (Johansson *et al*. 2006). Transporting fuel chips over long road distances was only competitive when chipping at the terminal, since there are lower chipping costs at terminal (Johansson *et al*. 2006).

2.7.1.3 Technology costs

Technology costs are a function of capital and operational costs that depend on resources, scale, location, and other factors (ECN 2014). For many energy conversion technologies, the cost of electricity production reduces as scale increases (ECN 2014)- economies of scale. This is also true for large-scale anaerobic digestion biogas systems (ECN 2014). The cost of installing and operating a biomass electricity generation plant for example, depends highly on the size of the system (IRENA 2012). Power generation is less competitive at a smaller scale, because the cost of operation and maintenance per unit tends to be higher (IEA 2012). Larger plants, on the other hand, while offering economies of scale, require significant amounts of feedstock and this leads to increasing transport distances and material costs (IRENA 2012).

By contrast, use of biomass for heat generation in CHP plants is a cost competitive option (IEA 2012). CHP plants allow for an economic use of heat produced in biomass power generation (IEA 2012). Although the use for biomass for heat is a significant opportunity and is often the more viable route of utilising biomass then the generation of electricity for small-scale applications (IEA Bioenergy 2015), the scope of this study only covers the supply of biomass for the generation of electricity. Heat generation is mostly viable where there is a steady demand for heat. Despite the fact that South Africa does not have high demand for heating applications (unlike colder climates of European countries), there is also an opportunity to use the biomass heat to drive cooling processes (adsorption chilling), but this technology is poorly commercialized Economies of scale

Scale is arguably the one of the biggest barriers to an economic biomass operation (Eco-Invest ABI 2015). The nature of biomass-based operations requires scale as it deals with a bulky, yet low value added operation (Turpie 2014; ECN 2014; Eco-Invest ABI 2015). Bioenergy can be produced in both centralized and decentralized conversion plants at a small or large-scale (Amigun *et al*. 2010). However, biomass feedstock by virtue of its low energy density cannot take full advantage of economies of scale in the power plant because low energy density limits transport distances to the power plant (IRENA 2012). Sorensen (2005) and von Doderer (2012) stated that decentralized bioenergy plants are preferred, as they enhance the use of local resources and have greater potential to create local employment. Within the context of IAP clearing operations, scale can only be achieved by pooling the resources of different landowners to ensure that there is a sustainable supply of feedstock. STEAG Energy Services (2013) found that decentralized power plants were well suited for geographically integrated systems within bush encroached areas of Namibia.

3 Materials and methods

3.1 Species selection

Thirteen non-woody IAPs were collected and characterised, namely Sisal (*Agave sisilana*), Giant reed (*Arundo donax*), Saltbush (*Atriplex nummularia*), Castor-oil plant (*Ricinus communis*), Queen of the night (*Ceres jamacaru*), Inkberry (*Cestrum laevigatum*), Chromoleana (*Chromoleana odorata*), Water hyacinth (*Einchornia crassipes*), Lantana (*Lantana camara*), Sweet prickly pear (*Opuntia ficus-indica*), Pickerel weed (*Pontederia cordata*), PB Cassia (*Senna didymobotrya*) and Bugweed (*Solanum mauritianum*). The invasive plants were collected from different climatic zones within South Africa - in the Western Cape, Kwa-Zulu Natal and Mpumalanga. The species list was compiled by merging the lists of the top invasive species from all provinces of South Africa, as identified by various studies (Le Maitre 2000; Henderson 2007; Invasive Species South Africa 2016). Most of these studies were conducted on behalf of the NRM programme of the Department of Environmental Affairs.

A description of the species selected for this project is given in Appendix 1, together with the origin of each species, its effect on biodiversity and the extent to which they have invaded ecosystems in South Africa (www.agis.agric.co.za).

3.2 Sample collection and preparation

Plant material of between 0.5-1 kg was collected in sealed plastic bags to prevent loss of moisture. The plastic bags were labelled with the common plant names. The samples consisted of the whole plant as it was extracted, where possible, i.e. the leaves (dead/live), flowers and the stem to ensure a representative sample collection. Prior to fuel analysis the wet biomass samples were comminuted in an attrition mill to reduce particle size to a more homogenous size. Milling was the only comminution technology used in this study, as most samples were too small to be chipped. Once milled, the samples were dried to determine the moisture content (MC), and thereafter heating value (HV), ash content (AC), and volatile content (VC). For the elemental composition analysis the dry samples were further reduced to a size of 180 μm with a Retsch rotor mill and screened with a vibratory sieve to obtain a uniform particle size. Figure 4 illustrates the process of sample preparation.

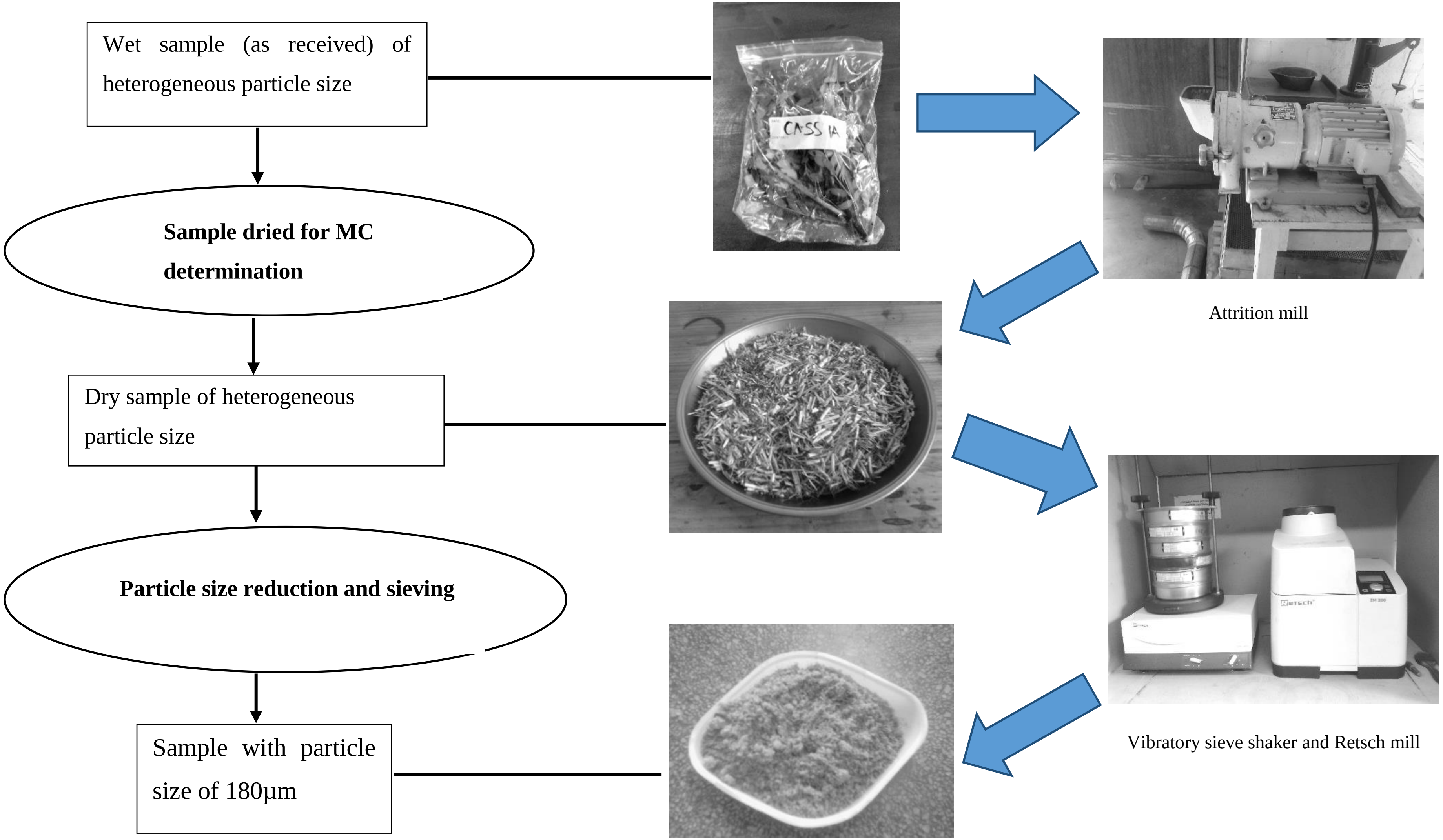

Figure 4: Procedure followed for sample preparation prior to proximate and elemental analysis.

3.3 Characterization of biomass

The most important properties of biomass, which determine the performance as a fuel when combusted, are physical parameters, such as MC, AC, VC, HV, bulk density and chemical composition (carbon, hydrogen and nitrogen content) (ECN 2014; Idaho National Laboratory 2016). These properties were evaluated according to the relevant standards and procedures, which are described below.

3.3.1 Determination of loose bulk density

The loose bulk density of the biomass was determined using a modified version of BS EN ISO 17828:2015, the standard method for determining bulk density of solid biofuels. The loose bulk density as received (BD_{ar}) was determined via shock impact. A cylindrical vessel (of 100 ml) was filled with biomass and solidified by shock exposure to allow the biomass to settle and then weighed. The loose bulk density of the wet material is given by equation1:

$$BD_{ar} = \frac{m}{V} \tag{1}$$

Where m = mass of the biomass in kg and V = occupied volume in m^3.

After the samples were oven dried the dry bulk density (BD_d) was determined again according to the BS EN ISO 17828:2015 standard.

The dry bulk density of the sample mass can also be calculated if the wet density is known, according to equation 2:

$$BD_d = BD_{ar} \times \frac{100 - MC_{ar}}{100} \tag{2}$$

BD_d= dry basis bulk density, MC_{ar}=moisture content as received

The dry bulk density might deviate from the calculated dry bulk density as the latter disregards shrinkage or expansion.

Reporting the bulk density as received (wet) is important for handling, storage and transport related costs. For energy conversion purposes on the other hand the bulk density on a dry basis is important (Meincken and Tyhoda 2014).

3.4 Proximate analysis

The proximate analysis consists of MC, VC, AC and HV. Each of these properties was determined from three replicates for all samples.

3.4.1 Determination of the moisture content

MC describes the amount of water in biomass. It is important as it affects costs throughout the value chain (Meincken and Tyhoda 2014). The MC can be determined on a wet basis or dry basis. All samples were weighed using a Mettler AE200 analytical balance. A sample of about 2-3g of the wet biomass was weighed and placed in a drying oven with natural convection from Memmert, type U40 at 103± 2˚C for 24 hours, or to constant weight. Subsequently, the sample was removed from the oven and cooled in a desiccator before the dry weight was recorded. MC was determined according to BS EN ISO 18134-2: 2015 using equation 3. For the purposes of this study the MC was reported on a wet basis, which means the maximum weight of wood and water is 100 % using equation 3.

$$MC = \frac{M_{wet} - M_{dry}}{M_{wet}} \times 100\% \qquad (3)$$

Where m_{wet}= wet sample mass and m_{dry}= dry sample mass.

MC_{wet} is important for economical purposes to determine transport costs and is mostly used in the bioenergy sector to describe biomass (Meincken and Tyhoda 2014).

3.4.2 Determination of the ash content

Inorganic residue such as silica, potassium, calcium, sulphur and chlorine make up the ash that remains after combustion (Meincken and Tyhoda 2014). AC determination was carried out according to BS EN14775:2009, the test method for determination of AC of solid biofuels. Ceramic crucibles were weighed empty and with dry biomass before being placed in a muffle furnace with a thermostat set at a controlled temperature of 575˚C for 3 hours. After cooling the samples were weighed again and ash content determined by differences in weight according to:

$$\mathrm{AC}\ (\%) = 100 \times \frac{\mathrm{m_{ash}}}{\mathrm{m_{dry}}} \tag{4}$$

m_{ash}= mass of ash, m_{dry} = mass of dry sample

3.4.3 Determination of the volatile content

Volatile matter is the gas that escapes when biomass is combusted. High volatility means that a large part of the biomass is vaporized before homogeneous combustion can take place, thereby lowering the calorific value.

The VC was determined using a modified version of BS EN 15148:2009. Ovendry samples of approximately 0.5g were weighed in a ceramic crucible with both the weight of the crucible and sample recorded. The samples were placed in a furnace for 5 minutes at 900˚C. After cooling, the remaining mass was weighed, and the volatile content determined according to:

$$\mathrm{VC}\ (\%) = 100 \times \frac{\boldsymbol{m}_{cruc} - \boldsymbol{m}_{remainingMass}}{\boldsymbol{m}_{cruc} - \boldsymbol{m}_{dry}} \tag{5}$$

m_{cruc} = mass of crucible, $m_{remaining\ Mass}$= mass of contents and crucible after heating, m_{dry}= mass of dry sample

3.4.4 Determination of the heating value

The energy content, also called heating value (HV), is the amount of thermal energy produced when biomass is burnt. It is measured in terms of the energy per unit mass, or volume in MJ/kg for solids, MJ/l for liquids, or MJ/Nm^3 for gases (McKendry 2002). The HV can be reported on two bases, the higher heating value (HHV), or the lower heating value (LHV). HHV refers to the total energy released when the fuel is burnt, it assumes that the water in the biomass has been evaporated and the energy recovered. The LHV, however, assumes that the energy from water vaporisation is not recovered (Meincken and Tyhoda 2014) and this is the case with most electricity power plants where the energy used to vaporise the water is not recovered. The HHV is useful to determine the maximum possible heating value, but practically the LHV should be used to calculate the potential for electricity production from biomass.

The HHV of the biomass was determined according to the ISO 1928 method with an ECO bomb calorimeter. A dry sample of about 0.5g was burnt in a lead bomb in an oxygen atmosphere of 3000 kPa. As the biomass combusts, a small temperature increase can be detected in the bomb that can be converted into the energy content per sample weight.

3.5 Elemental analysis

The ultimate analysis of a fuel consists of the elemental analysis (McKendry 2002). It reports the weight percentage of the main elements of interest contained in the biomass, in this study carbon (C), nitrogen (N), silica (Si), sulphur (S), and chlorine (Cl) content. Sheng and Azevado (2005), who correlated the HV of biomass with the elemental composition, reported that high C levels lead to an increased HV of biomass. Thus determining the C content in particular will give a good indication of the HV of biomass. High levels of N and S may result in high gaseous emissions. A high Cl content (and alkali content) may lead to corrosion of the reactor, which creates operational issues (BISYPLAN 2012), while a high Si content lowers the ash melting point and may lead to slagging in the reactor (McKendry 2002).

The elemental analysis was carried out by Bemlab in Somerset West South Africa. Bemlab is an independent accredited laboratory (South African National Accreditation System ISO 17025).

3.6 Feedstock Requirements

The amount of biomass required to supply 1MJ/s to an energy plant was calculated for all samples. One MJ was used as a base unit to allow easy comparison. The LHV at 30% MC (which is acceptable for most conversion reactors) was calculated according to equation 6 (Sokhansanj 2011).

$$\mathrm{LHV}_{30}[\frac{\mathrm{MJ}}{\mathrm{kg}}] = \mathrm{HHV} \times (1 - \mathrm{MC}_{30}) - 2.443 \times \mathrm{MC}_{30} \tag{6}$$

Where MC is the wet basis moisture content (mass fraction decimal).

1 MJ/s

1kg of Inkberry contains about 12.75 MJ/kg at 30% MC

1/12.75= 0.08 kg/s needed

(x3600) =>282.42 kg/hr

(x 24) =>6.78t/ day

(x 365) =>2474.04 t/year

(7)

3.7 Rating system

A multi-criteria decision-making system was used to rank the species. The first step was to calculate the criteria weights. Three criteria were used: processability, drying time required and amount of feedstock required (Table 3). The weighting of each criterion was calculated on an interval scale using the normalized criteria method proposed by Zangemeister (von Gadow and Bredenkamp 1992). The strength of each criterion was judged in terms of relative importance using an interval scale ranging from -3 to +3. For example, in the third column (highlighted in green) processing was judged to be two times less important than drying and feedstock requirements three times less important than drying. Reducing the moisture content of biomass early in the supply chain reduces costs further down the supply chain, including transport and other handling costs. Thus, drying time was seen as more important than processability and feedstock requirements. The scale values (highlighted in grey) represent the differences between the compared criteria, for example the difference between drying and processing using a scale ranging from –3 to +3 is two. The scale values for each criterion were then added up. The next step was to add a number (F) to each column, where F = T(n-1) and T represents the value of the highest possible score (von Gadow and Bredenkamp 1992), in this case 3. This is done to ensure that all the weights are positive (von Gadow and Bredenkamp 1992). Finally, the weights were normalized through division by the sum of the weights.

Table 3: Calculation of criterion weights (adapted from Ziesak 2013)

	Drying	Processing	Feedstock requirements
Drying		-2	-3
Processing	2		-2
Feedstock requirements	3	2	
Total	5	2	-2
Total plus F= (+6)	11	8	4
Weight (%)	47.8	34.8	17.4

After determining the weighting of each criterion, a rating system was developed as follows: For ease of processability samples were assigned values between 1 and 5, with 1 being difficult and 5 being easy. Plants were first cut with garden scissors to reduce them in size and then put through the attrition mill. Those with too soft plant parts and long fibres made processing difficult, as it clogged the mill, in which case they would be assigned a low rating. For drying time required and feedstock requirements the samples were also rated from 1 to 5, with 1 being worst and 5 being best. The MC value was used as an indicator of the required drying time, i.e. the highest MC would result in the longest drying time. The higher the value the better the species performed (e.g. Drying = 5 required least amount of drying time). The scores given to each species were multiplied by each criterion weight and added to result in the overall rating.

3.8 Modelling the delivered costs of the biomass feedstock

Cost modelling was performed to compare the cost of harvesting and transporting between the different biomass feedstock. Giant reed, Lantana, Bugweed, Saltbush, Inkberry, PB Cassia, and Chromoleana were selected for the economic evaluation. These seven species were selected, because they had the most suitable biomass properties for electricity generation via combustion. Calculations were performed in an Excel model adapted from the Flower Valley Study (Appendix 2) by Ackerman and Shuttleworth (2009). Clearing data was obtained from the NRM Information Management System (WIMS 2014), a database that estimates the overall costs of clearance (Marais and Wannenburgh 2008), whilst the costs of transportation were obtained from the Flower Valley study by Ackerman and Shuttleworth (2009/2016). The costs obtained from the calculations in this study refer to the costs of supplying the biomass fuel at 30% MC, excluding biomass costs, contingency costs, management costs, and profit margins for landowners or contractors.

3.8.1 Biomass harvesting

A WfW team is usually responsible for felling the trees in many clearing operations of IAPs. The NRM approach and methodology to clearing IAPs uses the WIMS programme, which records all clearing data including the alien species name, densities, plant size, habitat type, costs and person days planned to work in a specified area (Marais and Wannenburgh 2008). The database records more than one species and its density per polygon. Seven density classes, which are based on aerial canopy cover are used in the database, namely: rare (0- 0.1%), occasional (0.1- 1%), very Scattered (1-5%), scattered (5-25%), medium (25-50%), dense (50-75%) and closed (75-100%).

The norm and standards from WIMS differentiates between the size and growth form of the species (adult, young and seedlings) to assign treatment methods and estimate the costs of labour (van Wilgen *et al*. 2016). This information is important, as the size of the plant has an impact on the treatment method and the treatment cost. It further gives the person days 'requirement per hectare according to the growth form of the invasive plant. The database allocates costs per treatment to the dominant species per polygon, which determines the number of planned person days needed to complete the task. According to NRM clearing guidelines (DEA 2015b) large plants (>1m in height) of Bugweed, Inkberry, Triffid weed, Lantana, PB Cassia, Chromoleana, and Saltbush need to be cut (using bow saws, loppers and chainsaws) at ground level.

Since the exact stand density distribution of the 13 species in this study is not known in South Africa, the species were grouped under 'herbaceous growth form' and the cost per hectare for clearing was calculated for each density class. The treatment method selected from the norm table for an adult herbaceous plant was cut and spray. The PD rate required to clear adult herbaceous plants at different densities is presented in Table 4.

Table 4: Person days (pds) required per hectare to clear herbaceous IAPs at various densities (WIMS 2014)

	Rare	Occasional	Very scattered	Scattered	Medium	Dense	Closed (100%)
PD rate	0.001	0.110	0.550	1.783	3.370	7.780	10.370

To calculate the clearing cost per hectare per species, the species growth form was identified and then the person day allocation and PD rate were multiplied to obtain the cost per hectare (equation 8). The cost per person day for NRM clearing (human resources and running costs) is R380.81 (Braak 2016).

$$\text{Cost/ha}= \text{PD rate} \times \text{Pds} \tag{8}$$

Where Pds= person days per area and PD rate =cost per person day (R380.81).

3.8.2 Transport

Transport costs are a function of capital costs (haulage truck) and operating costs (labour fuel, maintenance). For transporting loose chips a 6×4 Rigid Drawback trailer-truck was used as reference. The truck hauling capacity is 56 000 kg (Ackerman and Shuttleworth 2009/2016) with two containers with internal volume of 33 m^3 and 67.5 m^3. According to Ackerman *et al*. (2014), container systems are best suited for transporting loose chips, although they have a high tare weight. Another advantage of container systems is that at the chipping site they are easily exchangeable, which reduces the downtime for both the truck and the chipper (Ackerman *et al*. 2014). Technical data for the truck (including average travel speeds loaded and empty) was adopted from the Flower Valley Study. In the Flower Valley Study transport cost was determined over four radii: 10 km, 20 km, 30 km and 40 km. For this study the average transport costs (R/ (t*km)) for each species were used. Transport costs to supply biomass in R/GJ were calculated using an average (25 km) suitable transport distance (equation 9). According to Zafar (2013) transport distances from source to conversion plant beyond a 25-50 km radius are deemed uneconomical.

$$\text{R/GJ} = \frac{\text{Feedstock for 1MJ/s (t)}}{\text{Avg. transport costs (R/(t} * \text{km))} \times 25} \tag{9}$$

3.8.3 Economic viability of using non-woody IAPs for electricity generation

Determining the financial viability of using non-woody IAPs for energy generation is relevant to assist in decision making (ECN 2014). The presented cost estimates reflect the costs to supply the biomass to an energy plant gate. Actual electricity generation costs were not included. The input data in the financial viability analysis included the harvesting, chipping and transport costs of delivering the chipped biomass to a conversion plant. Harvesting (R176/wet tonne) and chipping costs (R149/wet tonne) were derived from the study by Mugido *et al*. (2013). The lower costs were used because of the large variation in price and cost instability. These costs were then inflated to present producer price index (PPI) values in 2016 (liberta.co.za) of R208/wet tonne and R176/wet tonne for harvesting and chipping respectively (see Appendix 3). Equations 10 and 11 were then used to calculate the average cost (per GJ) of supplying the power plant with biomass.

$$\mathrm{R/GJ} = \frac{\text{Harvesting costs}\left(\frac{\mathrm{R}}{\mathrm{t}}\right)}{\text{energy content}\left(\frac{\mathrm{MJ}}{\mathrm{kg}}\right)} \tag{10}$$

Chipping costs were also calculated with an equation similar to equation 12:

$$\mathrm{R/GJ} = \frac{\text{Chipping costs}\left(\frac{\mathrm{R}}{\mathrm{t}}\right)}{\text{energy content}\left(\frac{\mathrm{MJ}}{\mathrm{kg}}\right)} \tag{41}$$

A R/GJ cost was calculated by adding the costs obtained from equations 9, 10 and 11 together to obtain the supply chain cost for each species, to allow comparison of the different IAPs with each other and also with other biomass types, such as woody IAPs and plantation residue and also to determine whether or not supply costs of non-woody invasive are a viable option for electricity generation.

4 Results and discussion

To evaluate the suitability of non-woody IAPs as feedstock for different energy conversion processes, the properties of the biomass materials were determined. This included the proximate analysis (MC, AC, VC and HV) and the ultimate analysis (elemental composition).

A summary of the results is given in Table 5 together with a rating of the ease of processability.

4.1.1 Heating value

The HV is directly related to the chemical composition, with the main contributing elements being C, H, O and S (Munalula and Meincken 2009). A high C content contributes positively to the HV (Meincken and Tyhoda 2014); while H, O, and S have a negative effect on HV. A higher O and H content lower the HV of a fuel, because they result in a higher VC (McKendry 2002). The HHV of woody biomass typically ranges between 18 and 20 MJ/kg (Meincken 2011) while the HHV of the biomass samples in this study varied between 13.3 MJ/kg (Queen of the night) and 19.3 MJ/kg (Inkberry). The high HV of Inkberry, Chromoleana (17.2 MJ/kg) and Giant reed (17.1 MJ/kg) can be linked to their higher C content and lower MC.

Table 5: Proximate and ultimate analysis and processability of biomass samples

Species	Proximate analysis (%)			Elemental analysis					HHV (MJ/kg)	Processability				
	MC	Ash	VC	C (%)	N (%)	S (ppm)	SI (ppm)	Cl (ppm)		1 Difficult	2	3	4	5 Easy
Giant reed	49.2±1.2	3.4±0.6	97.0±0.7	51.9	0.9	1566.6	91.8	2308.8	17.1±0.2					5
Lantana	73.6±2.2	5.8±0.2	83.4±7.1	57.0	2.6	2138.0	270.7	3108.0	16.9±0.3					5
Pickerel weed	84.3±0.1	6.9±0.3	91.2±0.6	46.2	2.2	1127.3	199.3	16747.6	15.9±0.3			3		
Castor-oil plant	84.3±1.5	5.6±0.9	96.8±1.1	56.3	5.8	3609.2	53.5	6322.6	16.4±0.5					5
Sweet prickly pear	92.4±0.1	8.3±0.8	90.7±0.2	50.7	0.9	935.7	64.5	15682.1	16.0±0.4			3		
Bugweed	65.7±3.3	4.1±1.0	95.8±0.7	43.3	3.0	1528.9	31.6	7690.1	16.9±0.2					5
Saltbush	54.9±1.9	14.2±0.3	86.2±0.2	44.3	1.5	1900.7	43.7	1642.8	16.1±0.4				4	
Inkberry	70.9±0.6	6.3±0.3	93.4±0.9	56.6	2.0	2314.7	284.9	4031.5	19.3±0.9					5
PB Cassia	70.0±0.2	6.2±0	94.1±0.5	54.6	2.3	1693.8	221.9	4422.2	16.9±0.1					5
Chromoleana	61.6±2.0	4.7±0.5	94.4±1.1	58.6	1.4	1579.9	24.0	9004.3	17.2±0.1					5
Water hyacinth	94.7±0.1	17.1±1.2	85.5±0.8	36.7	3.2	2262.1	41.7	16925.3	13.9±0.1	1				
Queen of the night	87.5±0.2	16.6±0.4	84.6±0.4	43.1	0.6	1990.7	117.9	603.8	13.3±0.1	1				
Sisal	83.3±0.3	9.2±0.2	91.3±0.6	60.4	0.8	557.4	108.2	692.6	17.4±0	1				

4.1.2 Loose bulk density and processability

The wet and dry bulk densities for this study ranged between 82.04 kg/m^3 to 915.35 kg/m^3 and 28.56 kg/m^3 to 216.46 kg/m^3, respectively (Table 6). The density of Sweet prickly pear, Queen of the night, Castor-oil plant, Pickerel weed, and the Sisal plant as received were very high, because of their high MC, which translated into high transport costs. The dry bulk densities were generally low, but compared well with non-woody biomass feedstock studied by Tanger *et al*. (2013). Bulk density not only impacts the transport costs, it also has an effect on the processability (comminution) of the biomass (Tangler *et al*. 2013). Processability (Table 5) was used as a first decision step to discard the species, which were difficult to comminute, as a resource for combustion. Sweet prickly pear, Water hyacinth, Queen of the night and Sisal had soft plant parts that clogged the mill and made processing complicated. The long fibres of the Queen of the night plant were also problematic during comminution. In addition, Sweet prickly pear also had thorns, which had to be removed before milling.

Table 6: Loose bulk density per species

Species	**Wet density (kg/m^3)**	**Dry density (kg/m^3)**	**%MC**
Giant reed	86.67	60.48	49.2
Lantana	155.87	60.75	73.6
Pickerel weed	119.45	28.56	84.3
Castor-oil plant	253.12	63.75	84.3
Sweet prickly pear	915.35	216.46	92.4
Bugweed	163.70	42.11	65.7
Saltbush	82.04	167.25	54.9
Inkberry	298.89	138.67	70.9
PB Cassia	200.48	80.39	70.0
Chromoleana	196.03	108.05	61.6
Water hyacinth	160.61	44.21	94.7
Queen of the night	804.26	168.71	87.5
Sisal	642.22	110.01	83.3

4.1.3 Moisture content

MC has a direct, negative effect on the conversion efficiency of biomass (Meincken 2011), as well as on its storage durability and potential self-ignition of the storage pile. Fuel moisture is a limiting factor in biomass combustion due to its negative effect on heating value.

The MC_{wet} for all analysed plants was very high and varied between 49.2% and 94.7%. Biomass cannot be combusted when it is too wet, in which case it needs to be dried (Meincken 2011; ICFR 2013). MC values below 50%, but preferably below 30% are required for thermochemical conversion technologies (McKendry 2002), as fuel with high MC causes a decrease in the energy output, because energy is used to evaporate moisture. As a result, transport and fuel costs increase, as more volume needs to be transported for equivalent net energy for combustion (IRENA 2012). Hughes and Larson (1998) argued that although drying prior to conversion increases the overall efficiency, the gains in efficiency decrease with the required level of drying.

According to Caputo *et al*. (2005) biomass with a MC above 50%, such as herbaceous plants are better suited to a wet conversion process, such as anaerobic digestion and fermentation. For further analysis Sweet prickly pear, Water hyacinth, Queen of the night, Sisal, Pickerel weed and Castor-oil plant were discarded as they had a too high MC and would require very long drying times, before they could be further processed. They would, however, still be feasible for energy production through anaerobic digestion.

Giant reed (49.2%), Saltbush (54.9%) and Chromoleana (61.6%) had comparatively low MCs, resulting in high CVs of 17.1 MJ/kg, 16.1 MJ/kg and 17.2 MJ/kg, respectively.

4.1.4 Ash content

Wood without bark usually contains <1% ash (Munalula and Meincken 2009), while faster growing biomass like straw and hay contain 5-10% ash (Stahl *et al*. 2003). The acceptable ash limit for gasification reactors according to the European standard is 0.7 %. The ash content of the biomass analysed in this study ranged from 3.4±0.6 % to as high as 17.1±1.2 %, as shown in Table 5.

The high AC of all analysed species makes them unsuitable for gasification, which is highly sensitive to ash amount and composition. Ash related problems in combustion reactors include corrosion, fine particulate emissions and ash slagging (McKendry 2002). Several of the lower AC and MC samples may, however, be considered for combustion.

The HV as a function of AC is displayed in Figure 5 and it can be seen that they are inversely related. When biomass with a high AC is combusted, a smaller amount of its mass is converted into energy, as only the organic matter contributes to the energy output.

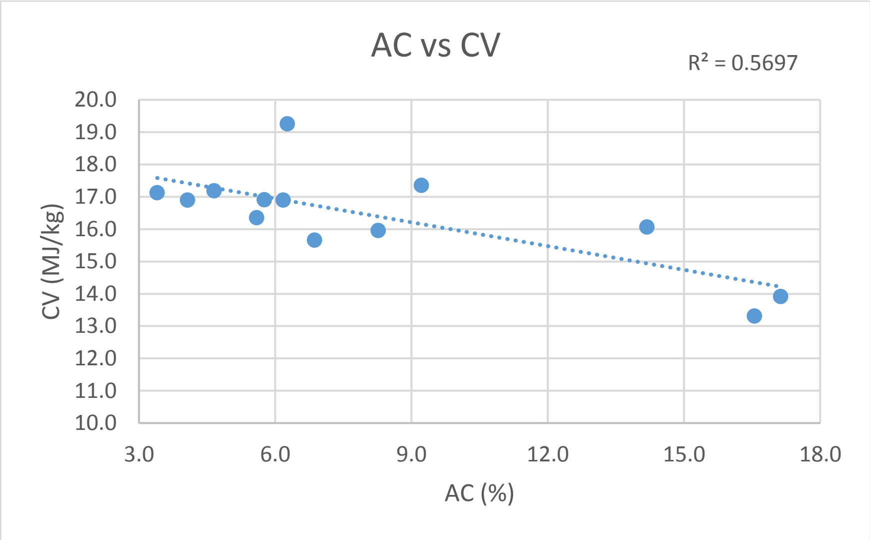

Figure 5: The effect AC on HV.

4.1.5 Volatile content

The VC consists of the organic matter that escapes in gas form when biomass is heated and for combustion a low VC is preferred. The VC of biomass is typically around 60-90% (ICFR 2013). A high VC means that a large part of the biomass is vaporized before homogenous combustion can take place and if the vapour is water it, leads to a lower HV (Meincken and Tyhoda 2014). All analysed species were highly volatile with VCs above 80%, as shown in Table 5, and can therefore not be considered for pyrolysis or char coal production. They might, however, be suitable for gasification, combustion, or bio-chemical conversion. The VC of Lantana, Saltbush, Water hyacinth and Queen of the night are comparable to the VC of woody biomass.

4.2 Ultimate analysis

4.2.1 Carbon content

For thermochemical energy, conversion a high C content is desirable, as it is positively correlated to the HV (McKendry 2002; Munalula and Meincken 2009). The results obtained in this study also confirmed this, as shown in Figure 6.

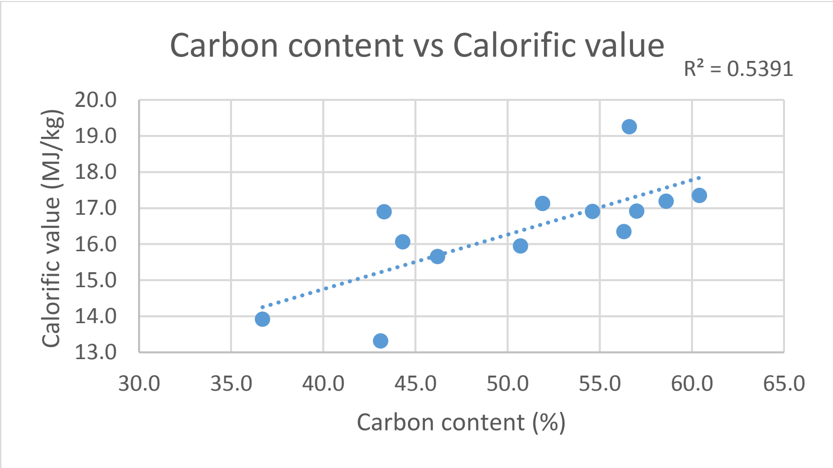

Figure 6: Effect of C content on HHV for the 13 species tested.

Sisal (60.4%), Chromoleana (58.6%), Lantana (57.0%) and Inkberry (56.6%) had C contents comparable to woody biomass and correspondingly high HVs. Water hyacinth (36.7%), Queen of the night (43.1%) and Pickerel weed (46.2%) had a lower C content and subsequently a lower energy content of 13.9 MJ/kg, 13.3 MJ/kg and 15.7 MJ/kg, respectively. However, since CO_2 is one of the main products of combustion a high C content can also be an indication of potentially high carbon emissions (Smit 2010).

4.2.2 Si, Cl, N, and S content

Undesirable elements in ash such as Si, Cl and S need to be as low as possible as they cause chemical reactions that might affect the reactor. They can cause problems, such as slagging and corrosion in reactors. Slag forms when Si melts into hard, glassy patches. Cl and S form alkali chlorides, resulting in corrosion of the metal reactor. The content of these elements should therefore be as low as possible (Meincken and Tyhoda 2014). A high N content is also problematic, as N reacts with O to form NO, NO_2 and nitric acid, which are toxic and harmful to the environment (Munalula and Meincken 2009). Therefore, biomass with low nitrogen content is preferable. Table 7 shows the Si, Cl, S, and N content (rounded to the next full digit) in the analysed biomass and the European limits for pellet production (EN plus-A1). Although they are very stringent, the European standards for pellet combustion were used, as currently no comparable values are available for South Africa.

Table 7: Elemental composition non-woody IAPs and European limits (European pellet council, 2013)

Species	**Si (ppm)**	**N (%)**	**S (ppm)**	**Cl (ppm)**
	No limit given	≤ 0.3	≤ 500	≤ 200
Giant reed	92	0.9	1567	2309
Lantana	271	2.6	2138	3108
Pickerel weed	199	2.2	1127	16748
Castor-oil plant	54	5.8	3609	6323
Prickly pear	65	0.9	936	15682
Bugweed	32	3.0	1529	7690
Saltbush	44	1.5	1900	1643
Inkberry	285	2.0	2315	4032
PB Cassia	222	2.3	1694	4422
Chromoleana	24	1.4	1580	9004
Water hyacinth	42	3.2	2262	16925
Queen of the night	118	0.6	1991	604
Sisal	108	0.8	557	693

The N content of all the species was above the acceptable limit allowed by the European standard for pellets (EN plus-A1). The Castor-oil plant (5.8 %), Water hyacinth (3.2 %) and Bugweed (3.0%) had the highest N content, while Sisal, Queen of the night and Giant reed presented the best alternative. Si in biomass causes operational difficulties, as mentioned above. Allowable levels for Si are difficult to estimate as they depend on the level of other alkali metals in the biomass (Tanger *et al*. 2013) and the reactor that is used.

The Cl, N, S and ash content of all species exceeded the limit for pellets in compliance with EN 14961-2 within the class ENplus-A1, as shown in Table 7. Although Sisal had relatively low levels of N, S, and Cl compared to the other species, its long fibres clogged the mill and made it difficult to process (mill).

None of the analysed species can therefore be considered for thermochemical conversion, which makes use of sophisticated reactor designs, due to high S, Cl and ash content. The species could be suitable for further processing via biochemical pathways for ethanol or methane production and combustion in a simple furnace setup is might still be a feasible process to generate electricity.

4.3 Feedstock required to supply 1MJ energy

Table 8 shows the species that were found suitable for combustion and the amount that would be necessary to supply biomass at a rate of 1 MJ/s to a power plant. These species had a relatively low MC and high C content, which translates to a high HV.

Table 8: The amount of biomass feedstock required to supply biomasss at a rate of 1MJ/s to a power plant

Species	**HHV**	**MC**	**LHV_{30}**	**kg/s**	**kg/h**	**Amount dry weight (t/day)**	**Amount dry weight (t/year)**
Giant reed	17.13	49.19	11.26	0.09	319.84	7.68	2801.76
Lantana	16.91	73.63	11.11	0.09	324.14	7.78	2839.44
Bugweed	16.90	65.70	11.10	0.09	324.41	7.79	2841.82
Saltbush	16.07	54.87	10.51	0.10	324.41	8.22	2999.50
Inkberry	19.26	70.91	12.75	0.08	282.42	6.78	2474.04
PB Cassia	16.90	69.97	11.10	0.09	324.34	7.78	2841.23
Chromoleana	17.19	61.58	11.30	0.09	318.58	7.65	2790.77

Inkberry (highlighted dark grey) as feedstock would require the least amount of biomass per year, whereas Saltbush (highlighted light grey) requires the most feedstock. There was no significant difference in the LHV and feedstock required of Giant reed, Lantana, Bugweed, PB Cassia and Chromoleana

The density, ease of processability and amount of drying required would therefore be the deciding factor on which species are best suitable for electricity generation.

4.4 Rating

Table 9 shows the final rating of the species regarded as feasible for combustion based on processability, drying time and feedstock required. The ease of processability was rated between 1 and 5 from difficult, to easy. The drying time was judged based on the original MC and the feedstock required was taken from Table 8. They were rated from best (5) to worst (1) and weighed as follows: processability (34.8%), drying time (47.8%) and feedstock requirements (17.4%). The species with the highest final rating is the preferable species for combustion.

Table 9: Performance rating for the species suitable for combustion

Species	Criterion weight			Final rating
	47.8	34.8	17.4	
	Drying	**Processability**	**Feedstock requirements**	
Giant reed	239.1	173.9	69.6	482.6
Lantana	47.8	173.9	52.2	273.9
Bugweed	143.5	173.9	52.2	369.6
Saltbush	191.3	139.1	17.4	347.8
Inkberry	95.7	173.9	87.0	356.5
PB Cassia	95.7	173.9	52.2	321.7
Chromoleana	143.5	173.9	69.6	387.0

According to this ranking, Giant reed (highlighted dark grey) is the preferred species with a score of 482.6, followed by Chromoleana, Bugweed, Inkberry, Saltbush, PB Cassia, and Lantana. Lantana (highlighted light grey) performed worst with a rating of 273.9, due the longer drying time it required.

4.5 Economic analysis

4.5.1 Clearing and transport costs

The effect of density on the cost of clearing is shown in Table 10. As expected the costs of clearing increase with the density of invasive alien plants. The costs vary from R41.88 to R3 948 per ha, with an average of R1 520 per ha. The costs of clearing can also differ depending on the species concerned (Marais *et al*. 2004). For example, from the R3.2 billion budget in 2008 the cost of clearing Lantana, Chromoleana, Bugweed and Giant reed was R180.6, R171.8, R121.5 and R8.2 million, respectively (van Wilgen *et al*. 2012).

Table 10: Clearing costs (R/ha) for different invasion density classes

	Rare	**Occasional**	**Very scattered**	**Scattered**	**Medium**	**Dense**	**Closed (100%)**
PD rate	0.001	0.110	0.550	1.783	3.370	7.780	10.370
Cost/ha (R)	0.419	41.89	209.45	679.02	1283.33	2962.70	3948.00

The transport costs (Table 11) were calculated as R/(t*km) taking into account each species' wet density, as listed in Table 6.

The transport cost was calculated for four distance radii: 10 km, 20 km, 30 km and 40 km and the average cost was determined. The average unit costs varied between R6.33/t*km and R22.17/t*km, with an estimated average transport cost of R12.59/t*km.

Saltbush and Giant reed had the highest unit costs, while Inkberry had the lowest transport costs. These values do not compare well to the transport costs of woody biomass, which varies from R1.09/t*km and R4.63/t*km for distance radii between 30 km and 50 km (Mugido *et al.* 2013), but infield drying could be used to reduce the moisture content prior to transport.

Table 11: Costs for transporting biomass

Species	Cost (R/t.km)				
	Transport distances (km)				
	10	20	30	40	Average
Giant reed	33.79	16.89	11.26	16.89	19.71
Lantana	19.01	9.50	6.34	9.50	11.09
Bugweed	19.01	9.50	6.34	9.50	11.09
Saltbush	38.01	19.01	12.67	19.01	22.17
Inkberry	10.13	5.06	5.07	5.06	6.33
PB Cassia	15.21	7.60	5.07	7.60	8.87
Chromoleana	15.21	7.60	5.07	7.60	8.87

The estimated transport costs to supply 1 MJ/s energy to a power plant for Giant reed, Lantana, Bugweed, Saltbush, Inkberry, PB Cassia and Chromoleana are given in Table 12. The transport costs per MW were determined by assuming an average distance of 25 km from the harvesting site to the energy plant. The low densities and resultantly very high transport costs of the IAPs do not compare well with woody biomass feedstock and transporting low density and high moisture biomass creates logistical problems.

Table 12: Summary of the estimated transport costs of the different species.

Species	MC (%)	Wet density (kg/m^3)	HHV (MJ/kg)	Feedstock needed to supply biomass at a rate of 1 MJ/s (t/year)	Av. transport costs (t/km)	Transport costs R/GJ
Giant reed	49.19	86.67	17.12	2801.76	19.71	5.69
Lantana	73.63	155.87	16.91	2839.44	11.09	10.24
Bugweed	65.7	163.7	16.9	2841.82	11.09	10.25
Saltbush	54.87	82.04	16.06	2999.50	22.17	5.41
Inkberry	70.91	298.89	19.25	2474.04	6.33	15.63
PB Cassia	69.97	200.48	16.9	2841.23	8.87	12.81
Chromoleana	61.58	196.03	17.19	2790.77	8.87	12.59

Inkberry (highlighted dark grey) had the highest transport costs (R/GJ) followed by PB Cassia and Chromoleana. This can be explained by the higher wet density of Inkberry (298.89kg/m^3) compared to the other species. Transporting Saltbush and Giant reed (highlighted light grey) was the least expensive, due to their low wet densities.

4.5.2 Profitability of supplying non-woody IAPs for electricity production

To investigate the profitability of supplying biomass to an energy plant, the total costs in R/GJ per species from stump to energy plant gate were estimated and compared to other bioenergy feedstock, such as residue material from plantations and woody invasive plant biomass. Table 13 shows the total costs per MJ for each species. These were determined by adding the chipping, harvesting and transport costs. The total costs from stem to plant gate ranged from R28.13/GJ to R35.59/GJ.

Table 13: Harvesting, chipping and transport costs (R/GJ) of non-woody IAP biomass

Species	Harvesting cost (R/GJ)	Chipping costs (R/GJ)	Transport costs (R/GJ)	Total supply chain costs (R/GJ)
Giant reed	12.15	10.29	5.69	28.13
Lantana	12.30	10.42	10.24	32.96
Bugweed	12.31	10.42	10.25	32.98
Saltbush	12.95	10.97	5.41	29.33
Inkberry	10.81	9.15	15.63	35.59
PB Cassia	12.31	10.42	12.81	35.54
Chromoleana	12.10	10.25	12.59	34.93

According DEA (2015a) harvesting costs make up 49% of total costs on average. This is also evident in this study as the harvesting costs contributed the most to the total costs. The most widely used harvesting methods by NRM to clear IAPs are labour intensive and often linked to low productivity rates which increase harvesting costs (Kitenge 2011). A more mechanised approach could reduce the costs of clearing; however, this would result in less job opportunities (WfW IPP 2015). The cost of chipping was the second biggest contributor to the total costs. The study made the assumption that chipping took place infield. Perhaps chipping at the energy plant could offer lower costs, as was found in the study by Ofoegbu (2010). The transport of the biomass fuel has significant influence on the value chain (ICFR 2013). In this study however, the transport costs had the lowest contribution to the overall costs, because proximity of the power plant to the fuel source was disregarded in the calculation, as IAPs are scattered in the landscape.

Comparing the costs of non-woody IAP biomass supply for bioenergy with other types of feedstock, the logistical costs of the non-woody IAP biomass supply chain are more expensive.

Non-woody IAPs have a much lower energy density, thus the higher costs of biomass supply are expected. Ofoegbu (2010) estimated that the cost of chipping pine forest residue at a landing was approximately R3/GJ (with a HV of 18.44 MJ/kg). This study found that the chipping costs for non-woody IAPs ranged from R9.15/GJ to R10.97/GJ. The chipping costs of forest residue were lower in comparison with those of non-woody biomass found in this study.

In the study by Kitenge (2011) the chainsaw harvesting costs of woody IAPs ranged between R0.93/GJ and R2.34/GJ and chipping costs R1.16/GJ to R4.73/GJ (with an average HV of 19.49 MJ/kg). With respect to harvesting non-woody IAPs, the costs range was R10.81/GJ to R12.95/GJ and chipping costs R9.15/GJ to R10.97. Both the harvesting and chipping costs of woody IAPs were much lower compared to the non-woody IAPs from this study. The lower energy density of non-woody IAPs is the main contributor to the higher costs for non-woody IAPs.

The total supply chain costs of woody IAPs in Kitenge (2011), which included manual harvesting, motor-manual harvesting, extraction, chipping and road transport, ranged from R16.56/GJ to R35.39/GJ, with an average energy cost of R26/GJ. The average unit costs of coal are R11.05/GJ, with a minimum of R8.03/GJ and a maximum of R21.33/GJ (Department of Public Enterprise 2015). In comparison, the costs of supplying non-woody IAP biomass to an energy plant gate ranged from R28.13/GJ to R35.59/GJ, with an average of R 32.78/GJ. Given that the actual electricity generation costs were not included in this study, a thorough comparison of the effect on electricity price cannot be made with coal or the other biomass feedstock. However, from this study we can deduce that the costs of supplying non-woody IAPs for bioenergy are approx. 50% higher than that of coal or woody biomass.

One of the main reasons why electricity from the processing of a widely distributed feedstock, such as invasive species is not able to compete with biomass plants with centralised resources, such as sawmills, is because the feedstock needs to be harvested and transported to a conversion plant (WfW IPP Procurement Programme 2015). Thus NRM needs to establish more pilot projects that divide the country into areas for the utilization of biomass, in order to minimise the cost of transporting the biomass and also identify the most ideal site for the energy plants. This would also help when determining whether it is viable or not to invest in supporting projects in certain areas.

Partnerships between landowners, private sector and NRM are also key to making the biomass to energy value chain viable, particularly to spread the costs of harvesting the invasive plants through subsidies. With no assistance from NRM the estimated total operational costs of harvesting woody IAPs for electricity for a landowner could be as high as R62/GJ, but in partnership with the NRM programme, it could be reduced to between R25/GJ and R32/GJ (Mugido *et al*. 2014).

5 Conclusion and recommendations

5.1 Conclusions

One of the main driving forces behind the biomass for bioenergy initiative is ‘eradication by utilization’- that is to exploit the economic potential of invasive species and at the same time control their spread and eventually eradicate them (Borokini and Babalola 2012). The primary aim of the WfW programme is to clear invasive alien biomass and in doing so utilize the cleared biomass both in terms of value-added products and creation of jobs for the poor. The objective of this study was to identify the non-woody IAPs with potential to generate electricity and to evaluate the costs to supply non-woody IAP biomass to an energy plant gate.

The results of this study show that HV is not the only determining factor when evaluating biomass for bioenergy purposes. Other properties such as AC, N, Si, Cl, density, MC and ease of processability are also important. The non-woody IAPs analysed in this study were found to have higher MC, AC, VC, N, Si, S, Cl but lower density and HV than woody IAPs found in South Africa (Meincken and Munalula 2009; Smit 2010). Thus none of the species are suitable for gasification or pyrolysis and a large number of them has a too high MC to be suitable for combustion. These species could be recommended for energy conversion through bio-chemical conversion technologies, such as anaerobic digestion and fermentation.

Considering physical and chemical properties of the analysed biomass, the preferred species for combustion are Giant reed followed by Chromoleana, Bugweed, Inkberry, Saltbush, PB Cassia, and Lantana. The Sisal plant showed potential with the highest C content and a relatively high HHV, but a high MC, AC, VC, as well as difficulty with comminution make it unsuitable for combustion. Lantana, Bugweed and Chromoleana, which are among the top ten invasive species in South Africa have a good potential to be utilised for bioenergy production through combustion.

Inkberry requires the least biomass feedstock to generate 1MJ of energy per second, although the difference between the species was not very large.

Depending on the species and invasion density, initial clearing costs of non-woody IAPs ranged from R41.88 to R3948 per ha and transport costs ranged from R6.33/t*km to R22.17/t*km. The high transport costs were attributed to the high MC and low density of non-woody IAP biomass.

Giant reed was the best species based on its physical (processability, drying, HV), chemical (AC, N, Si, S, Cl) properties, and according to the economic analysis.

To consolidate the physical, chemical and economic optima, the top three species based on a compromise of the physical/chemical properties and costs were chosen. The economic viability was assigned a 40% weight, while the physical and chemical properties were assigned a weighting of 30% each. The species were ranked 1-7, from worst to best for each criterion. Table 14 shows the final rating based on physical, chemical and economic analysis.

Table 14: Consolidation of physical, chemical and economic analysis

Species	**Costs**	**Physical properties**	**Chemical properties**	**Overall rating**
Giant reed	1	1	1	1
Lantana	3	7	6	5
Bugweed	4	3	7	4
Saltbush	2	5	3	2
Inkberry	7	4	4	6
PB Cassia	6	6	5	7
Chromoleana	5	2	3	3

Giant reed, Saltbush, and Chromoleana (highlighted in grey) were the top three species based on all three criteria used. The economic analysis and the physical and chemical properties of Giant reed were far superior to the other species. The results of this study have shown that non-woody invasive biomass has the potential to be used as feedstock for electricity production through combustion. However, the feasibility study showed that using non-woody IAPs as feedstock for bioenergy production does not compare favourably with other biomass feedstock, such as forest residue and woody IAPs, as the logistics costs are too high. The financial analysis showed that the cost per GJ for harvesting, chipping, and transporting of non-woody IAP biomass is above that of other types of feedstock. Thus, although the NRM programme has created job opportunities in this sector, the value chain involving non-woody IAP biomass to energy do not yet offer a cost-effective way of supplying biomass for producing electricity.

The results of the analysis from this study are similar to many other studies. Barriers to the development of sustainable bioenergy generation, such as access, affordability and supply of biomass identified in this study also exist in other bioenergy value chains. Logistic operations have a big impact on the profitability of bioenergy production systems and the cost of logistic operations in bioenergy value chains is a major bottleneck for the utilisation of biomass. The low energy density of biomass has negative cost implications on the feedstock handling, pre-processing and transport. Furthermore, technology costs of dedicated biomass production systems are high in comparison with energy conversion technologies using conventional fuels. The environmental and socio-economic issues associated with bioenergy are, however, positive compared to fossil fuels. IEA (2012) reported that the inclusion of bioenergy in the future energy flux will be largely dependent on whether or not there are sufficient amounts of biomass feedstock available for heat, electricity and transport fuel production. Concerns over sustainability of transport biofuels (sugar cane, palm oil, starch) have been raised, because of the competition with the food market. However, the issue of sustainability is also relevant to other biomass feedstock, e.g. forest residue, invasive plants, wood fuel, etc., as it is not clear how much biomass is available globally for energy exploitation.

In order for bioenergy to become competitive with other energy sources, other economic factors need to be considered when making comparisons with alternatives, such as coal. Biomass production is often not evaluated in terms of the whole value chain or its wider impact- and is only evaluated in terms of comparative price to a low-grade, cheap alternative (Petrie 2014), not taking into account the external costs of coal- based power generation. External costs of coal-based electricity generation include effects on human health, water resources and contribution to climate change (Blignaut *et al*. 2011). The external costs associated with coal-generated electricity at the Kusile power station were valued to be between R31.2 billion and R60.6 billion a year (Blignaut *et al*. 2011). There is potential to reduce the negative impacts with the use of renewable energy sources, such as biomass. One of the key drivers to promote bioenergy is the reduction of greenhouse gas (GHG) emissions compared to the emissions of fossil fuels, such as coal (IEA 2012). The socio-economic aspects of bioenergy also need to be considered. Bioenergy use has considerable potential to create employment in the rural communities and along the supply chain. In developing countries such as South Africa, where they is a high dependence on agriculture for rural livelihoods there is potential to enhance this role and creating new, sustainable supply systems for biomass feedstock.

In closing, this study has shown that for bioenergy projects to become a viable option, some level of financial support is necessary to reduce the costs of harvesting. Strong governance and policy reforms are also needed to ensure the required investments for off-grid biomass electricity generation especially for rural areas in developing countries. Ultimately, the decision on the viability of IAP biomass to energy should focus on the socio-economic benefits.

5.2 Recommendations

Recommendations can be summarised as:

- Sweet prickly pear, Water hyacinth, Queen of the night, Sisal, Pickerel weed and Castor-oil plant were immediately discarded because of their high moisture. They could be converted to energy via anaerobic digestion for biogas production, which leaves scope for further research. Biogas production is a potentially suitable method for these species- as it is able to provide a number of useful products at a range of scales.
- None of the species can be considered for pyrolysis as they all have too high volatile content.
- None of the species can be considered for gasification, because of too high ash, Si, N, S and Cl content.
- The remaining species (Giant reed, Lantana, Bugweed, Saltbush, Inkberry, PB Cassia, and Chromoleana) may be considered for combustion in low technology reactors to produce heat and electricity via steam turbines.
- Giant reed, Saltbush, and Chromoleana are the best species to be utilised as feedstock, when considering physical, chemical and economic viability.

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Appendices

Appendix 1: Non-woody biomass characterized in this project (towns highlighted in yellow)

Agave sisilana (Sisal)

Origin: Central America (Mexico)

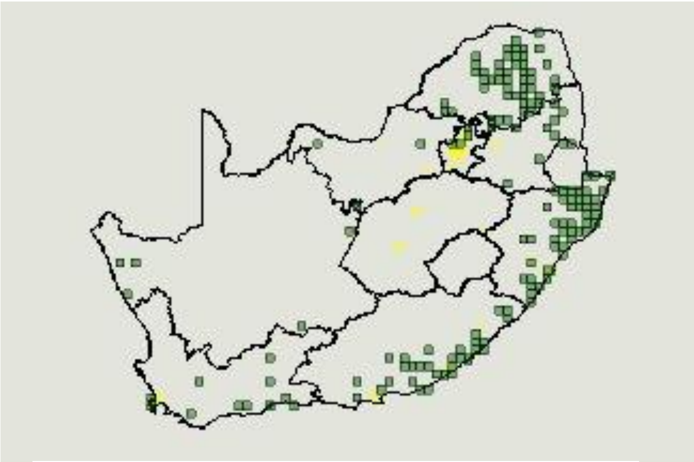
Distribution in SA: All provinces. Has become naturalised in South Africa. (Bromilow, 2001; Henderson, 2001).

Invasive status: Category 1: Declared weed (Henderson, 2001)

Plant details: The sisal plant has thick, sword-shaped leaves with conical spines at the leaf tips. The leaves are poisonous to animals, and its sap and spikes are irritant to the skin (Henderson, 2001).

Ecological threat: *Agave sisilana* invades and competes with indigenous species. Where plantations have been abandoned it forms impenetrable thickets making the land useless for grazing livestock (Bromilow, 2001).**Habitat invaded:** Tropical and subtropical savanna, bushland, erosion channels, and watercourses

Commercial use: Cultivated for a fibre known as sisal which is used to make rope, nets, mats, baskets, and sandals, as well as for security hedging and as a source of honey (Henderson, 2001;BioNET-EAFRINET).It is also used as a barrier in kraals and at some international borders (Bromilow, 2001).



Distribution of Sisal in South Africa
(www.agis.agric.za)

Arundo donax (Giant reed)

Origin: Asia (northern India)

Distribution in SA: All provinces. Present throughout the country's wetland areas.

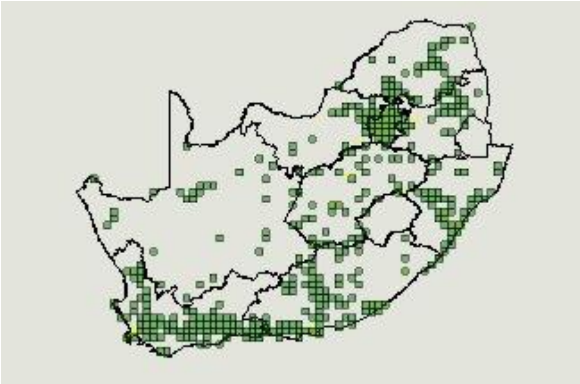
Invasive status: Category 1: Declared weed (Henderson, 2001)

Plant details: A large grass-like plant that produces bamboo-like stems and forms fairly dense stands which can reach 3-4 m in height. Although it is an obstructive plant it has ability to act as an erosion control agent and filter muddy floodwaters when in the right place (Bromilow, 2001).

Ecological threat: Due to its large biomass, height, and rapid growth it has potential to replace indigenous riparian vegetation (Guthrie, 2007). Since Fynbos is a fire-driven vegetation type is particularly susceptible to invasions by giant reed because of its ecosystem-changing capabilities (Guthrie, 2007). According to Guthrie (2007) giant reed has potential to invade more than a million hectares of the Fynbos biome.

Habitat invaded: Giant reed invades streams, drains, wetlands, riparian zones, and unlike indigenous weeds it can occur on sites away from water on roadsides (Henderson, 2001).

Commercial use: Ornamental, screening, ceilings, to carve musical instruments.



Distribution of Giant reed in South Africa (www.agis.agric.za)

Atriplex nummularia (Old man salt bush)

Origin: Central and SE Australia

Distribution in SA: The arid and semi-arid parts of the Western Cape, Eastern Cape, and Northern Cape.

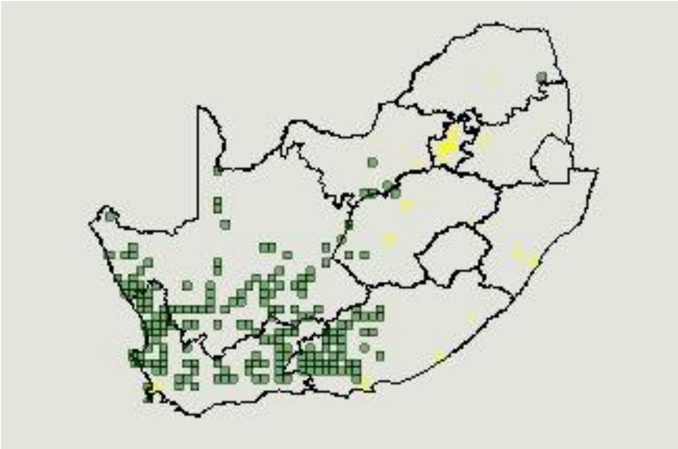
Invasive status: Category 2: Declared invader (Henderson, 2001)

Plant details: *A. nummularia* is an erect shrub with greyish-green scaly leaves; greyish flowers in compact; seeds enclosed in a papery capsule that turns pink when matured (Bromilow, 2001).

Ecological threat: Once established it competes with and has potential to replace indigenous fynbos (Bromilow, 2001).

Habitat invaded: Invasion of *A .nummularia* are commonly found in waste places and roadsides, sandy riverbeds, coastal dunes (Bromilow, 2001; Henderson, 2001a).

Commercial use: It is edible, nitrogen-rich and is cultivated for fodder. Stock farmers establish plantations of *A. nummularia* to make dry fodder during dry seasons when grazing land capacity is low (Bromilow, 2001).



Distribution of Old man Saltbush in South Africa (www.agis.agric.za)

Cerus jamacaru (Queen of the night)

Origin: South America (West Argentina, NE Brazil).

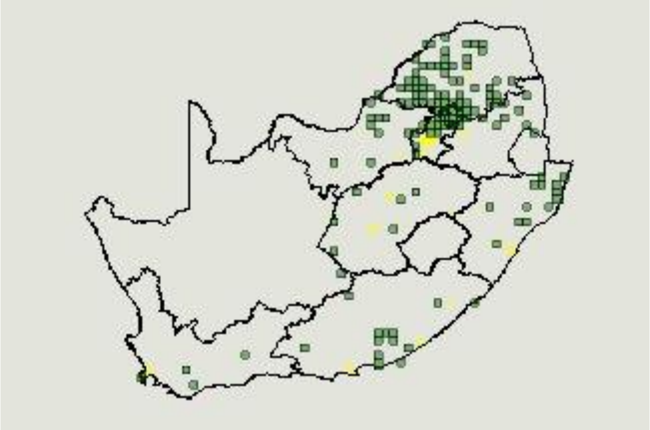
Distribution in SA: Although it is scattered in parts of Western Cape, Eastern Cape and Free State, it is more widespread in the warmer parts of Mpumalanga, Gauteng, KwaZulu-Natal, and Limpopo (Bromilow, 2001).

Invasive status: Category 1: Declared weed (Henderson, 2001)

Plant details: It is a spiny multi-stemmed succulent shrub can grow 6 to 7m tall (De Beer, 1987). Queen of the night as the name indicates opens its flowers at night and close again the next morning (Bromilow, 2001).
Ecological threat: Queen of the night a potential transformer of ecosystems. When it invades pastures it decreases the grazing potential of the land and prevents animals from grazing and finding shade (De Beer, 1987; Bromilow, 2001).

Habitat invaded: Savanna, rocky ridges (Henderson, 2001)

Commercial use: This cactus is cultivated for fencing and is grown as an ornamental plant in gardens because of its attractive white flowers.



Distribution of Queen of the night in South Africa (www.agis.agric.za)

Cestrum laevigatum (Inkberry)

Origin: South America (Brazil and Chile)

Distribution in SA: KwaZulu-Natal midlands, Mpumalanga, and has heavily infested the Hluleka Nature Reserve in Transkei.

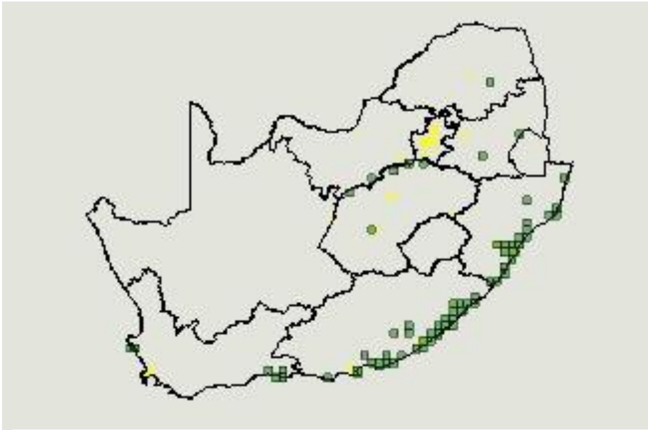
Invasive status: Category 1: Declared weed (Henderson, 2001)

Plant details: Cestrum laevigatum is an exotic evergreen shrub 1-2 m high in the Transvaal and Free State, or a tree up to 15 m high in the coastal areas (Henderson, 2001). It has glossy leaves, and branches from the base forming numerous stems.

Ecological threat: It transforms habitats and outcompetes indigenous plants (Bromilow, 2001). The whole plant of inkberry is poisonous. A cattle disease known as Chase Valley disease in Pietermaritzburg has been linked to inkberry poisoning (De Beer, 1986).

Habitat invaded: *C. laevigatum* invades moist areas in forests forming the undergrowth of plantations or on the fringes of indigenous forests or grows near streams and rivers in the drier inland areas (De Beer, 1986).

Commercial use: Ornamental, hedging



Distribution of Inkberry in South Africa (www.agis.agric.za)

Chromoleana odorata (Triffid weed)

Origin: North, Central, and Southern America (Henderson, 2001).

Distribution in SA: It has become prominent in the coastal regions of KwaZulu- Natal, Eastern Cape, Limpopo and Mpumalanga (Henderson, 2001; Bromilow, 2001).

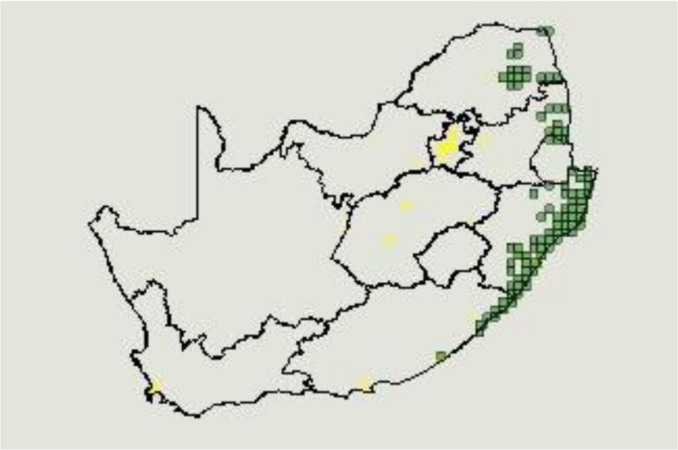
Invasive status: Category 1: Declared weed (Henderson, 2001)

Plant details: Triffid weed is a scrambling shrub with wide-spreading branches, and white or pale blue flowers. Its foliage is highly flammable and has a distinctive smell when crushed (Henderson, 2001).

Ecological threat: Its foliage is highly flammable and has a distinctive smell of paraffin or turpentine when crushed. It is in KwaZulu-Natal the greatest threat to biodiversity conservation, agriculture and forestry (Henderson, 2001).*C. odorata* is able to replace indigenous vegetation and thereby reduce grazing for herbivores. It limits access into plantations during the planting and harvesting phase, increasing the costs of production (Luwum, 2002).

Habitat invaded: It invades plantations, forest margins, riparian areas, savanna, and grassland biomes in SA, often forming dense thickets.

Commercial use: Ornamental



Distribution of Triffid weed in South Africa (www.agis.agric.za)

Einchornia crassipes (Water hyacinth)

Origin: Amazon Basin in South America

Distribution in SA: It was introduced to South Africa as an ornamental and has spread throughout the country affecting rivers in the Western and Eastern Cape, Mpumalanga, KwaZulu-Natal, and along the Vaal River in Gauteng and the Free State (Richardson and van Wilgen, 2004; Bromilow, 2001).

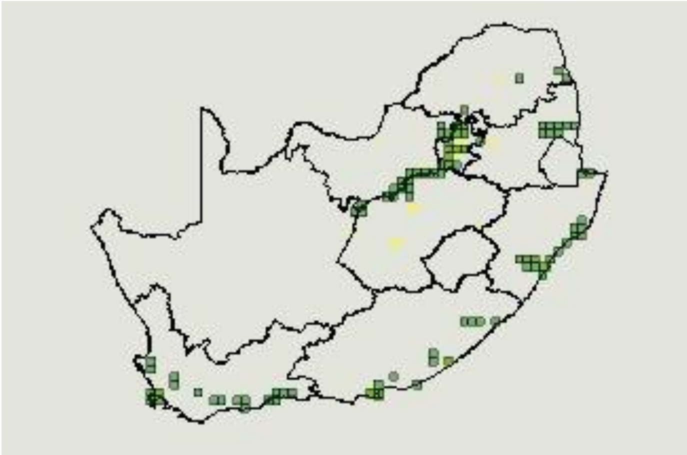
Invasive status: Category 1: Declared weed (Henderson, 2001)

Plant details: The aquatic weed either floats on the water surface or is anchored by hanging roots. When anchored it produces beautiful purple and violet flowers and seeds, doubling its population in 12 days (Lowe *et al*., 2000).

Ecological threat: The invasion of the aquatic weed affects irrigation and hydro-electricity facilities, fisheries, prevented navigation, and has even resulted in cattle drowning (Bromilow, 2001). Aquatic biodiversity is reduced as it prevents sunlight and oxygen from reaching the water surface (Lowe *et al*., 2000).

Habitat invaded: Water hyacinth spreads into lakes, dams, and rivers from windblown seeds and seeds washed down from upstream areas.

Commercial use: Ornamental



Distribution of Water hyacinth in South Africa

Lantana camara (Lantana)

Origin: Central and South America

Distribution in SA: Lantana can be found in all provinces except Northern Cape and Free State (Henderson, 2001).

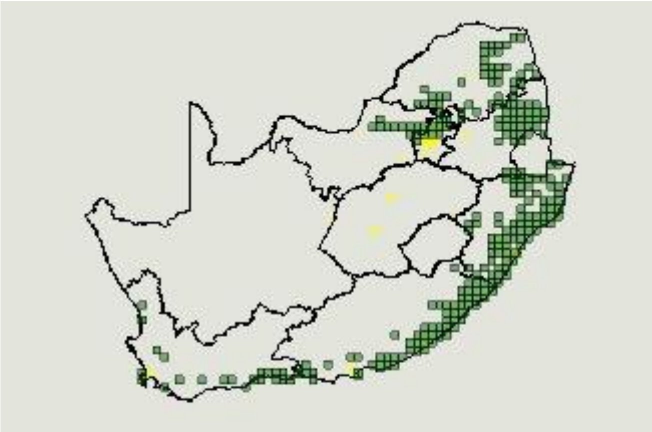
Invasive status: Category 1: Declared weed (Henderson, 2001)

Plant details: *Lantana camara* is a poisonous plant that is rated one of the world's 10 worst weeds (Wells and Stirton, 1988).

Ecological threat: Lantana grows well in full sun and can replace indigenous plants by growing over plants, reducing the grazing potential of the land, thereby increasing water run-off and erosion. The disturbed areas of the Natal coast and Transvaal Lowveld are most affected by Lantana. The weed is poisonous and may cause hair loss and skin damage in cattle (Wells and Stirton, 1988).

Habitat invaded: Lantana is found on the veld and plantations of KwaZulu- Natal coast with varieties of the weed in colder inland areas.

Commercial use: With over 50 different variants Lantana is a highly decorative garden plant which varies from a compact shrub to an untidy scrambler (Wells and Stirton, 1988). Its fruits are small and green, becoming purplish black when ripe (Wells and Stirton, 1988). Birds and animals such as monkeys and rodents spread the seed once it has been introduced to an area.



Distribution of Lantana in South Africa (www.agis.agric.za)

Opuntia ficus-indica (Sweet prickly pear)

Origin: Mexico

Distribution in SA: All provinces. The main areas of infestation in the country are from Aliwal North to Humansdorp in the Eastern Cape, but also stretches into Port St Johns, KwaZulu-Natal and Mpumalanga (Bromilow, 2001).

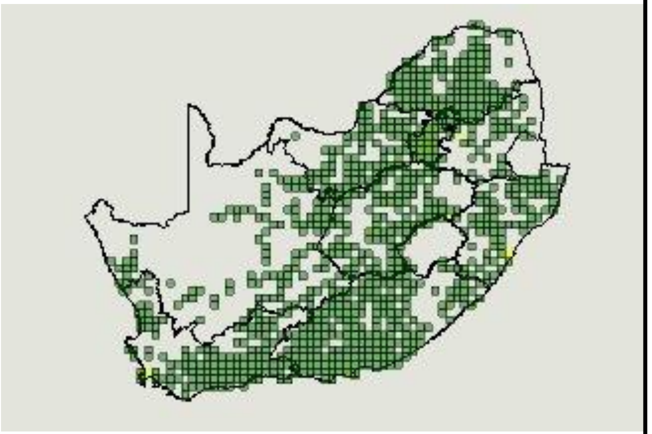
Invasive status: Category 1: Declared invader (Henderson, 2001)

Plant details: Its stems are divided into flattened and padded green cladodes armed with white spines (in the invasive form). Its showy, bright orange flowers open during the day giving rise to egg shaped fruits. A variety of spineless cultivars have been developed by South African farmers for fruit and fodder in the warmer drier areas (Bromilow, 2001).

Ecological threat: *O. ficus-indica* can be an aggressive invader and transformer of dry and rocky places in the savanna, thicket and Karoo, and causes injury to the eyes, mouths, and throats of livestock who consume its glochids (Bromilow, 2001; Beinart and Wotshela, 2001).

Habitat invaded: Mainly dry and rocky areas in savanna and Karoo biomes.

Commercial use: The sweet prickly pear is of high economic value to the Xhosa women of the Eastern Cape who continue to harvest it to sell its fruit (Beinart and Wotshela, 2001). The fruit of the spineless form (cactus pear) is believed to contain more vitamin C than apples, pears, bananas or grapes (Farmer's weekly, 2012).



Distribution of the Sweet prickly pear in South Africa (www.agis.agric.za)

Pontederia cordata (Pickerel weed)

Origin: North, Central and South America; America

Distribution in SA: KwaZulu-Natal, Mpumalanga, and Gauteng.

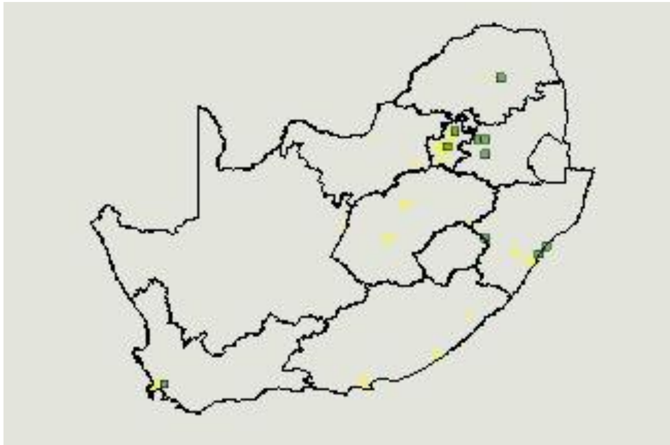
Invasive status: Category 3: Declared invader (Henderson, 2001)

Plant details: This aquatic invader is rooted growing up to 2m high forming colonies with its emergent stems and horizontal rhizomes (Henderson, 2001). The South African form is apparently sterile and does not produce flowers (Henderson, 2001; Bromilow, 2010).

Ecological threat: It is a vigorous grower able to fill a dam, thereby destroying biodiversity (Bromilow, 2010).This plant becomes problematic when it forms dense spreading clumps which block drainage canals, and interfere with crops on irrigated fields (Henderson, 2001).

Habitat invaded: It is a weed of dams, riverbanks, drainage lines and irrigated sugar cane

Commercial use: Ornamental



Distribution of Pickerel weed in South Africa (www.agis.agric.za)

Ricinus communis (Castor-oil plant)

Origin: Tropical E and NE Africa

Distribution in SA: All provinces

Invasive status: Category 2: Declared invader (Henderson, 2001)

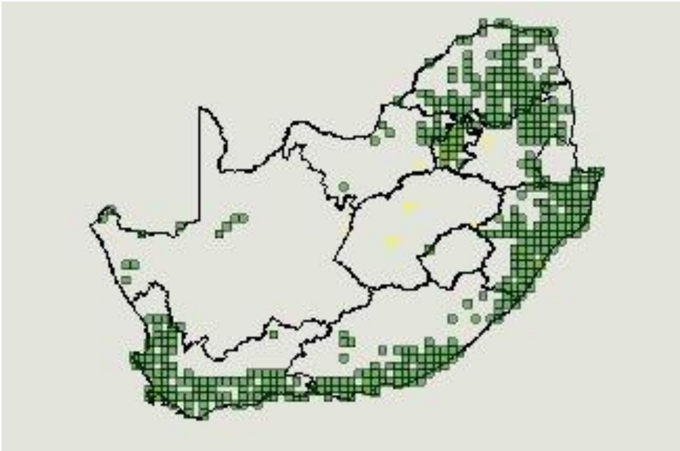
Plant details: The castor-oil plant is an annual herb, with a softly woody stem up to 4 m high. A very distinctive plant with shiny, dark green star-shaped leaves with serrated margins (Henderson, 2001).

Bromilow (2001) stated that since it occurs mainly in disturbed areas, its threat to indigenous biodiversity is minimal. Its seed is highly toxic to humans' animals.

Ecological threat: It is a poisonous shrub which competes with indigenous species.

Habitat invaded: It is common on riverbanks, roadsides, wastelands where is competes with indigenous pioneering species in watercourses.

Commercial use: cultivated for ornamental purposes and for castor-oil. The castor oil extracted from the seeds need to undergo purification as the plant is poisonous (Henderson, 2001; Bromilow, 2001).



Distribution of the Castor-oil plant in South Africa (www.agis.agric.za)

Senna didymobotrya (Peanut butter cassia)

Origin: Tropical Africa

Distribution in SA: Summer-rainfall regions, especially in the eastern parts of SA.

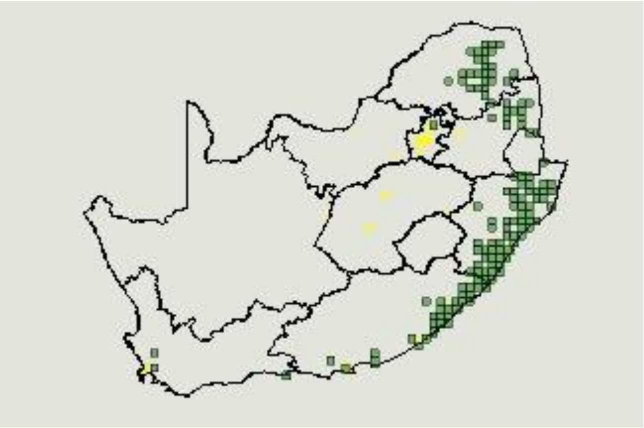
Invasive status: Category 3: Declared invader (Henderson, 2001)

Plant details: Flowers are bright yellow in upright racemes; green seed pods turn dark brown (Henderson, 2001). This perennial shrub reproduces by seed and invades grassland, coastal scrub, woodland, roadsides, and wasteland competing with indigenous plants. (Henderson, 2001).

Ecological threat: It is a poisonous shrub which competes with indigenous species.

Habitat invaded: Grassland, woodland, riverbanks, and wastelands.

Commercial use: Although it has poisonous leaves this *Senna* is cultivated for ornamental purposes and hedging (Henderson, 2001).



Distribution of Peanut butter cassia in South Africa (www.agis.agric.za)

Solanum mauritianum (Bugweed)

Origin: South America

Distribution in SA: All provinces except Northern Cape and Free State.

Invasive status: Category 1: Declared weed (Henderson, 2001)

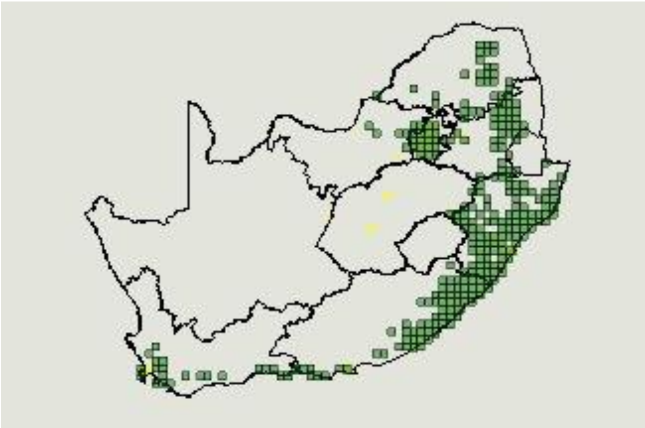
Plant details: a perennial weed with dull green leaves that release a strong smell when crushed. It can grow to reach a height of 3-5m shading out young trees in plantations, particularly pines and black wattle, stunting growth and causing stem deformation (Invasive species South Africa).

Its unripe fruits are poisonous; hairy stem and leaves are an irritant to the skin and respiratory tract (Henderson, 2001). Its poisonous fruit are a host of the KwaZulu-Natal fruit fly which eat and spread its seed (Bromilow, 2001).

Ecological threat: It is a transformer of habitats as it competes with indigenous riverine and young plantation trees.

Habitat invaded: Forest margins, plantations, savanna, and watercourses.

Commercial use: It was initially introduced to South Africa as an ornamental but is now also used to manufacture cheap furniture and shelves.



Distribution of Bugweed in South Africa (www.agis.agric.za)

Appendix 2: Flower Valley spreadsheet used for costing the transport costs.

	Chips	Solid Wood	Loose
Load size #1 (m^3) [1]	33	33	33
Load size #2 (m^3) [1]	67.5	67.5	67.5
Bulk density [2]			
Potential load at 40% MC (0.33 tonnes/m^3) (tonnes)			

Speeds travel[7]		
Loaded	Empty	Average
45	48	47

Multiplier [3]	1.19

Truck #3- 6x4 Rigid Drawbar		Gross weight	56000
Legal allowable limit	40000	Truck weight	16000

	2013	**2016**
Variable Cost [4]	6384.623	7604.1877
Fixed Cost [4]	3879.774	4620.8724

Cost components	**Distances (kms)**			
	40	**30**	**20**	**10**
Average travel time				
Load time (hrs) [5]				
Delay				
Unload time (hrs)				
Total time (hrs)				
Loads/day (8 hour/day)				
Potential loads/day [6]				
Chip Volume/day (t)				
Solid Wood Volume/day (t)				
Loose Volume/day (t)				
Total potential days/yr				
Chip Total potential (t/year)				
Solid Wood potential (t/year)				

Loose Volume/day (t/year)				
Distance (km/yr)				
Variable costs (R/km) [4]				
Fixed costs (R/yr) [4]				
Total annual costs (Rands)				
Annual costs (R/km)				
Chips Rand/tonne/km				
Solid Wood Rand/tonne/km				
Loose Rand/tonne/km				

Appendix 3: Cost structures in R/tonne

Harvesting and chipping costs from Mugido *et al*. (2013) were inflated to represent their present values in 2016.

Parameter	Units	Value	Source
Harvesting	R/Wet tonne	176	Mugido *et al*., 2013
Chipping	R/Wet tonne	149	

Inflation of costs				
Year	**2013**	**2014**	**2015**	**2016**
PPI inflation rate	0.0577	0.0613	0.0451	0.0657
Harvesting (R/Wet tonne)	**176**	10.80	8.42	12.83
Inflated value (R/Wet tonne)		186.80	195.21	**208.04**
Chipping (R/Wet tonne)	**149**	9.13	7.13	10.90
Inflated value (R/Wet tonne)		158.13	165.30	**176.13**

Summary of collection cost data (2016)		
Parameter	**Units**	**Value**
Harvesting	R/Wet tonne	208
Chipping	R/Wet tonne	176